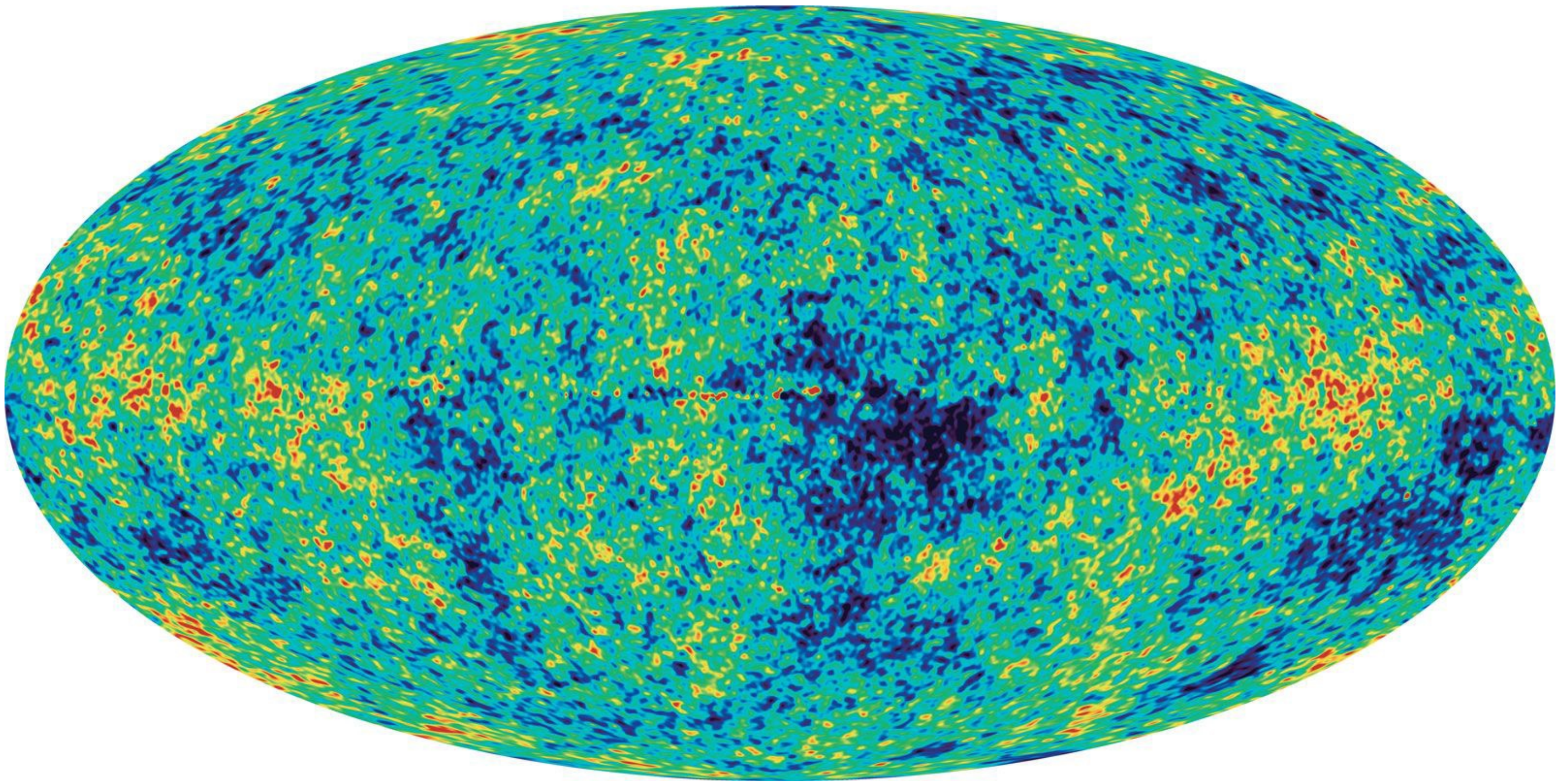
Shining lights through nuclear matter to see why they matter

- What we can learn from the Vector Meson Production

Kong Tu (BNL)

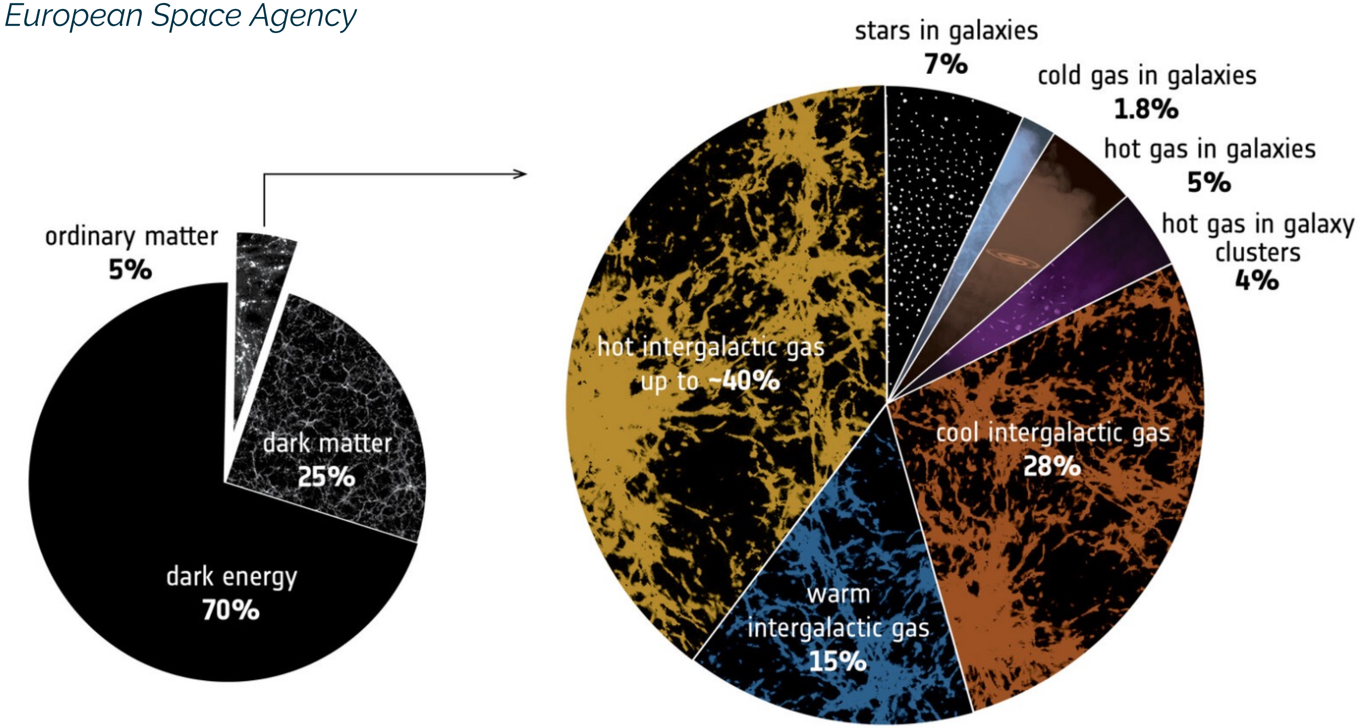
Our universe



Observable universe is ~ 93 billion light-years in diameter

What we can SEE in our universe

The cosmic budget of 'ordinary' matter
– European Space Agency



Only 5% of the universe is **visible matter**

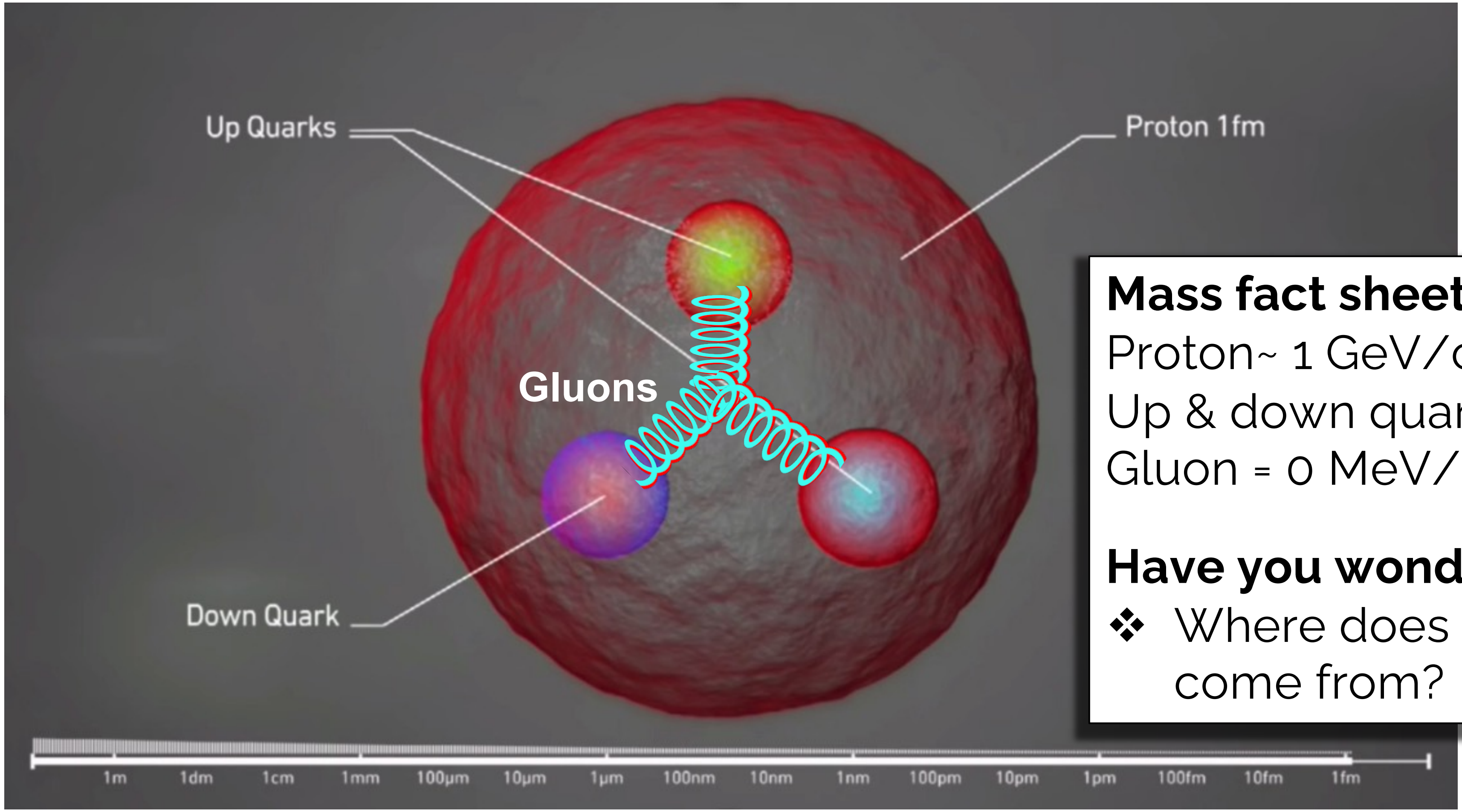
What is visible matter made of?

一花一世界，一叶一如来
《华严经》

A world in every flower, a Buddha in every leaf
- *Mahāvaipulya Buddhāvataṃsaka Sūtra*

(Video by CERN)

What holds them together?



Mass fact sheet:

Proton~ 1 GeV/c^2

Up & down quarks < 0.005 GeV/c^2

Gluon = 0 MeV/c^2

Have you wondered?

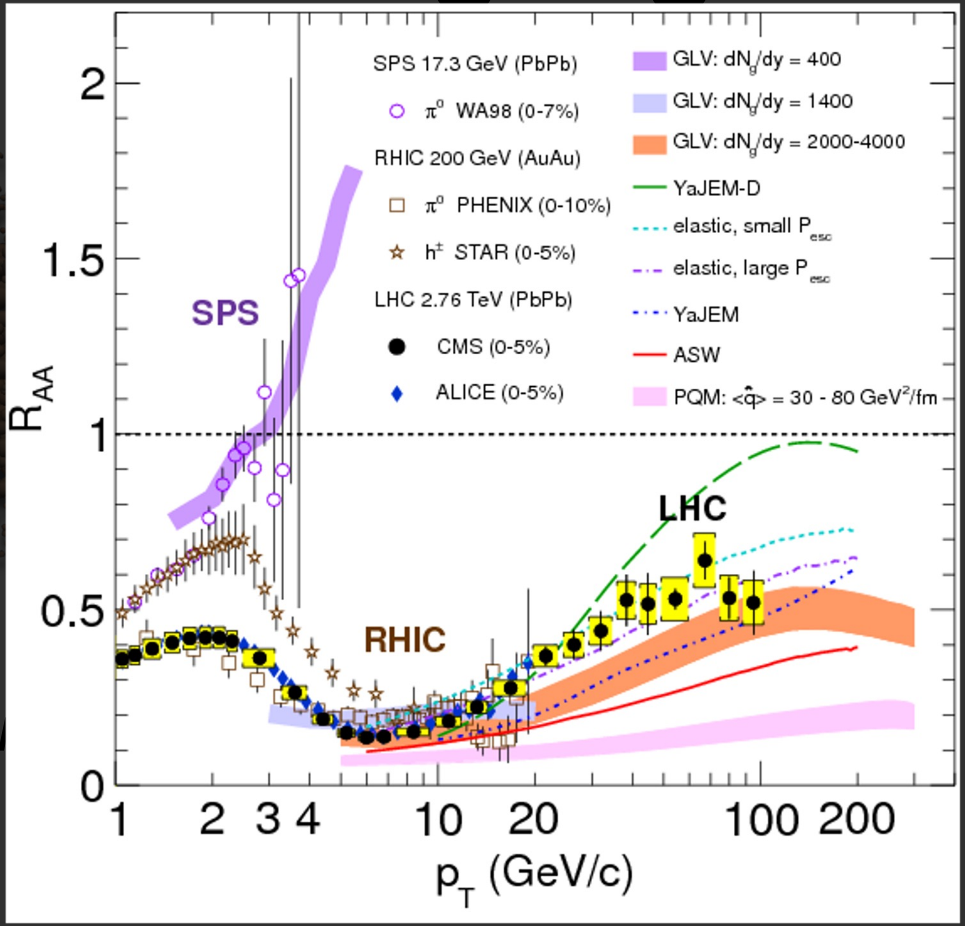
- Where does > 99% of proton mass come from?

Nuclear suppression from the hot Quark Gluon Plasma

Nuclei are ≠ nucleons sitting together

1) Heavy-Ion Collisions

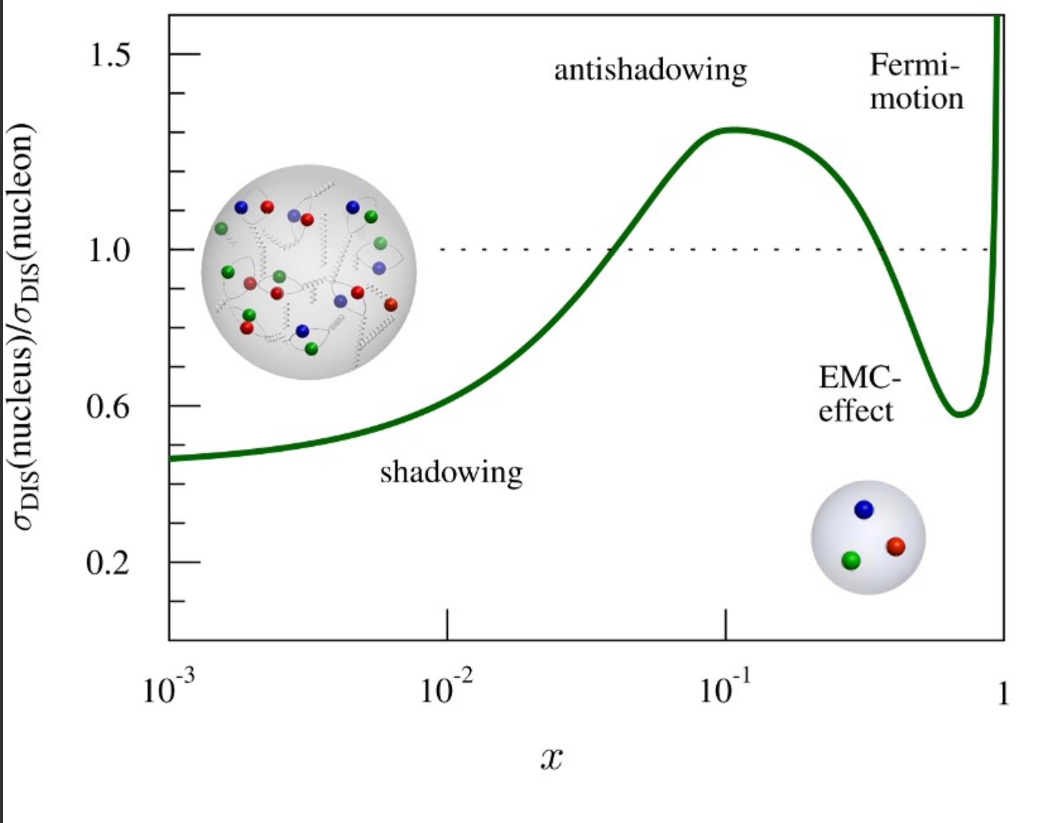
$$R_{AA} = \frac{N_{particle} \text{ in AA collisions} / (N_{col})}{N_{particle} \text{ in pp collisions}}$$



“..figuring out a pocket watch by smashi
observing the flying debris”

– Richard Feynman

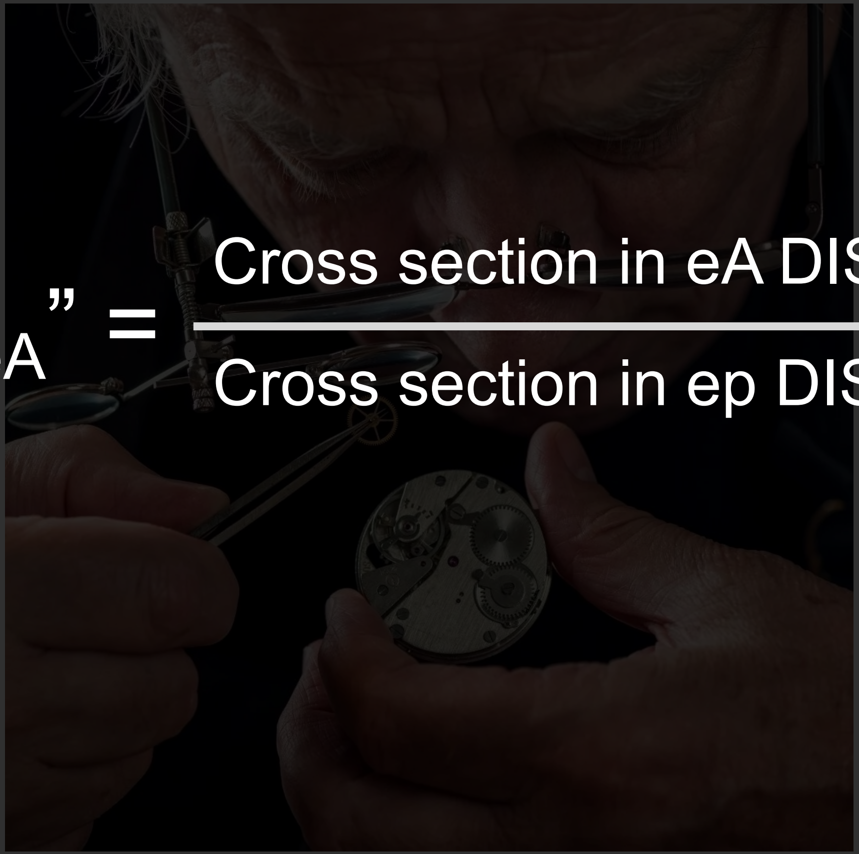
Nuclear suppression before the Quark Gluon Plasma



W

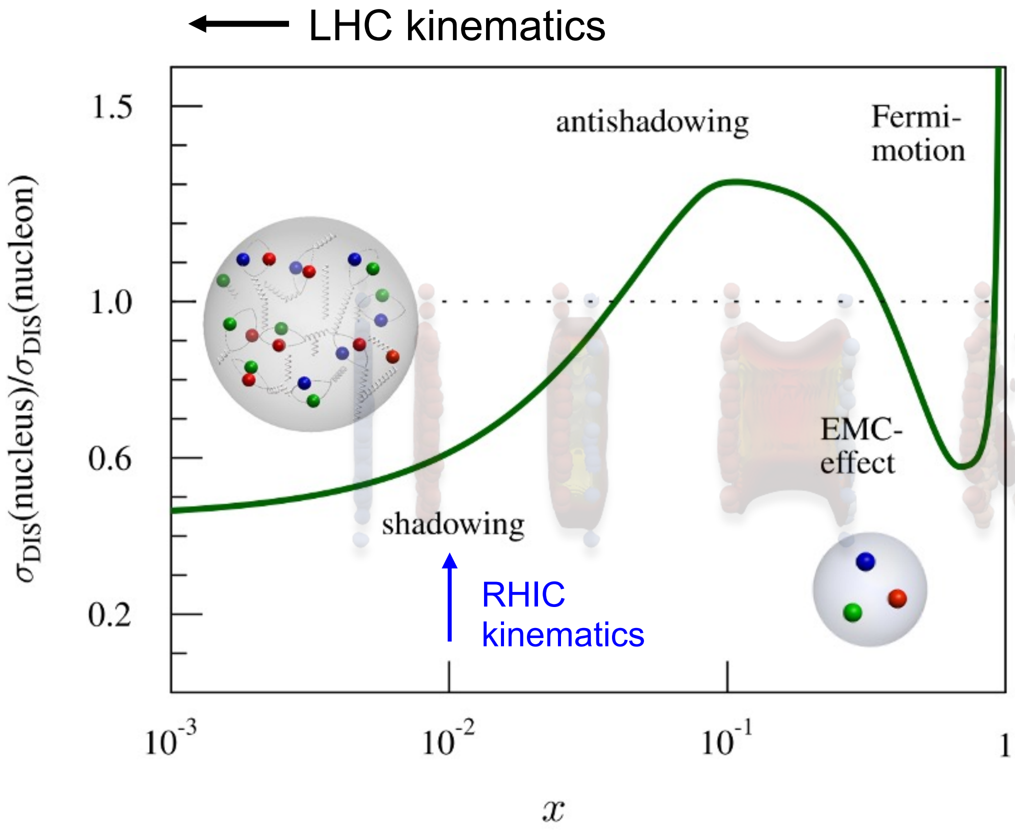
nucleus

Deep Inelastic Scattering (DIS)

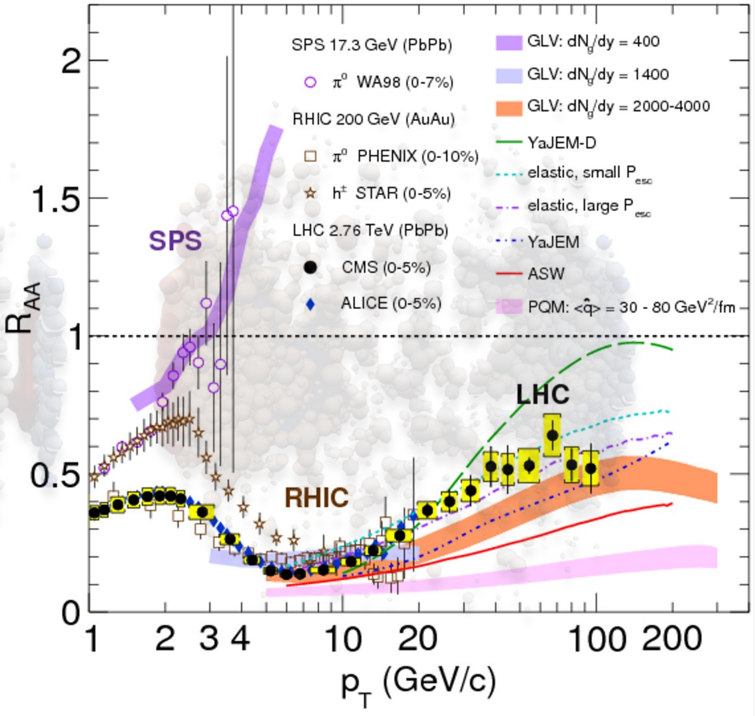


$$\text{“}R_{eA}\text{”} = \frac{\text{Cross section in eA DIS}}{\text{Cross section in ep DIS}}$$

This is where EIC and HI physics meets

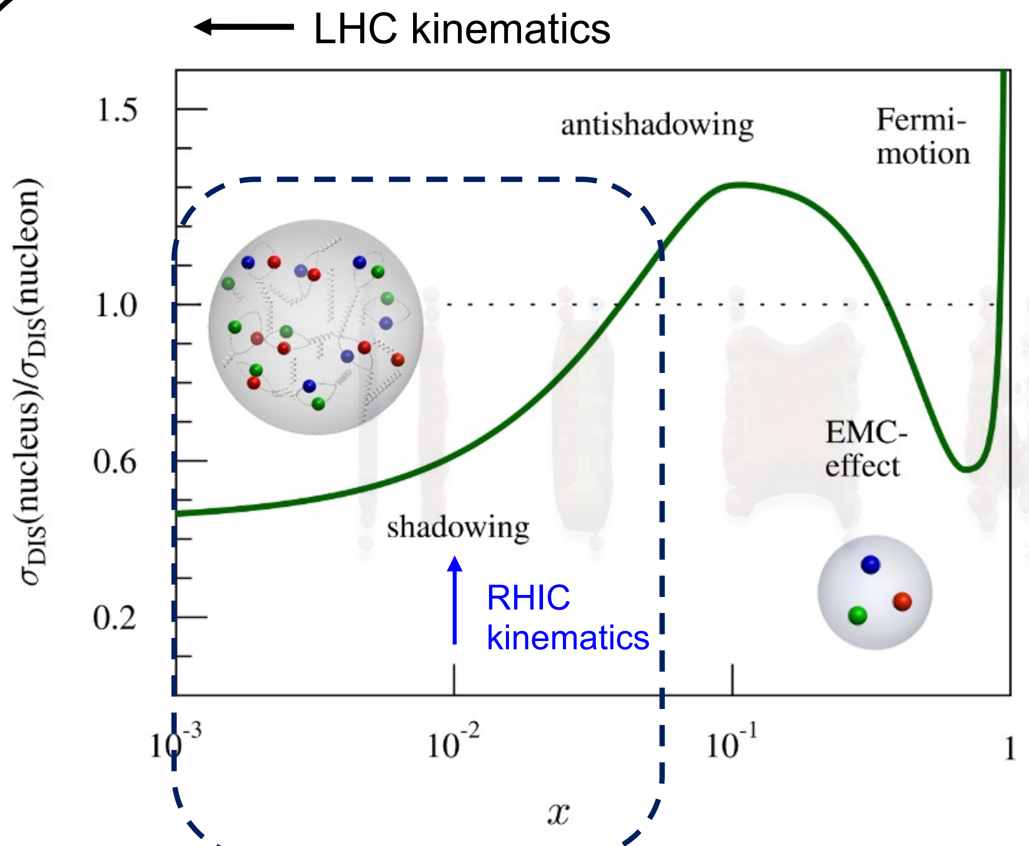


Initial state – cold QCD

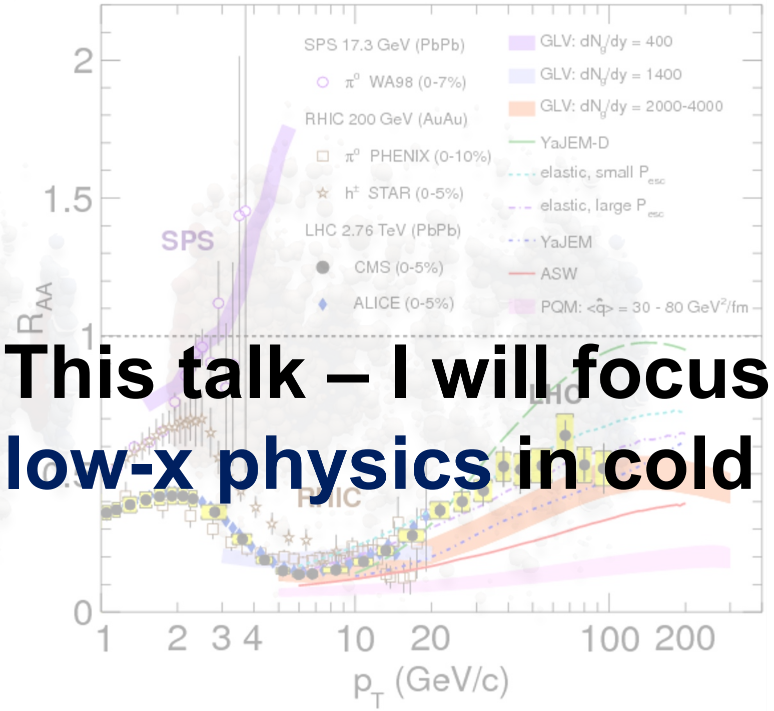


Initial + final state – hot QCD

This is where EIC and HI physics meets



Initial state – cold QCD

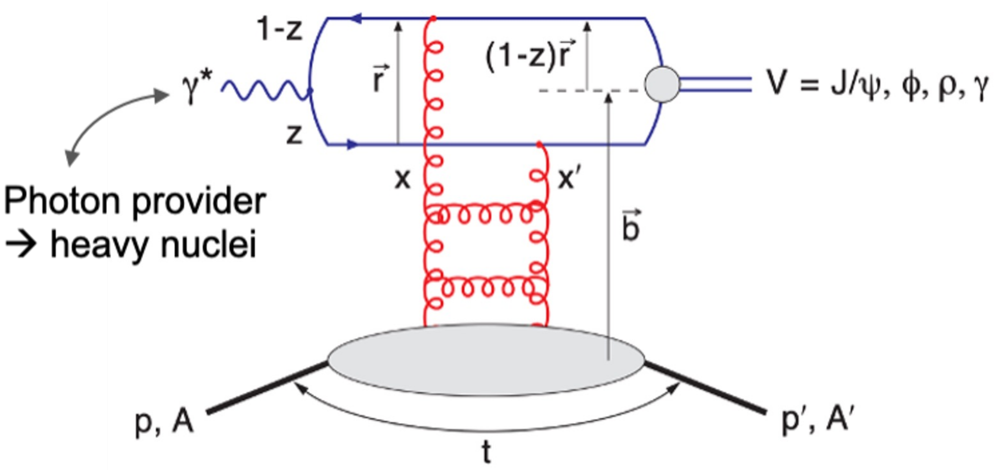


This talk – I will focus on low-x physics in cold QCD.

Initial + final state – hot QCD

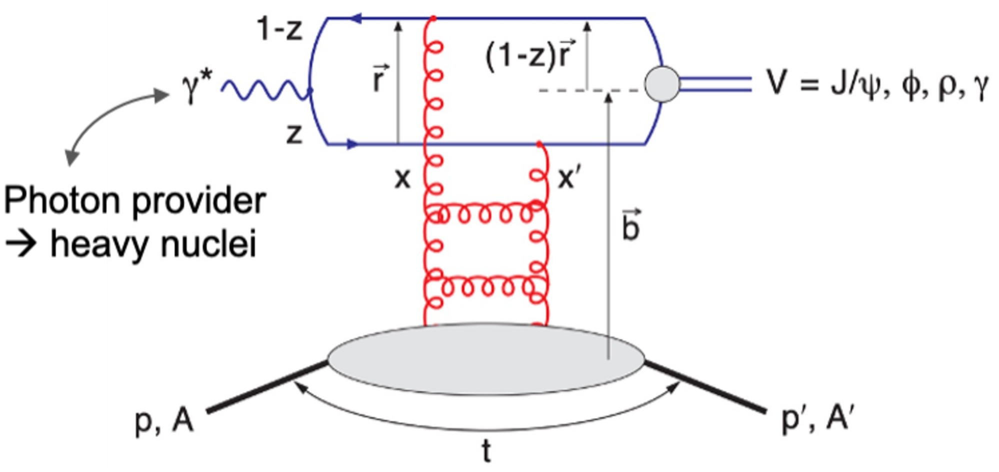
Vector Meson (e.g., J/ψ) production in heavy nuclei

At Leading Order, 2-gluon exchange



Vector Meson (e.g., J/ψ) production in heavy nuclei

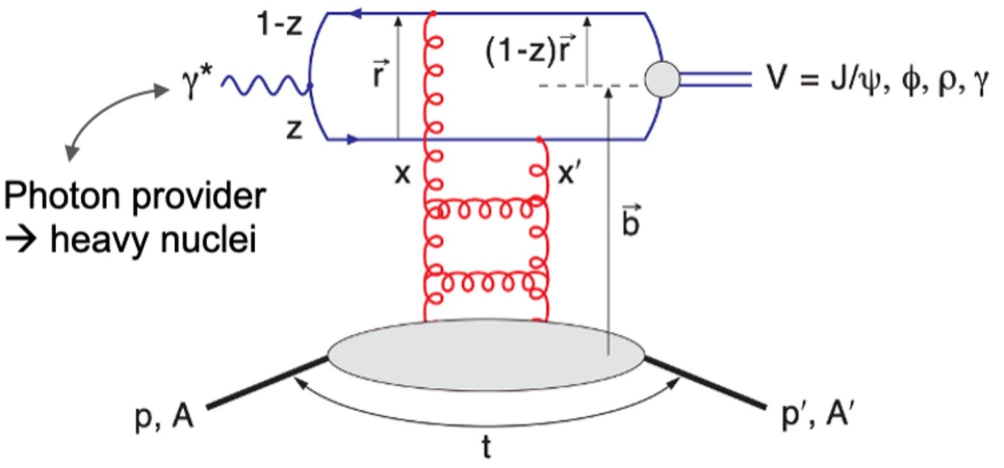
At Leading Order, 2-gluon exchange



Coherent (target stays intact)	Incoherent (target breaks up)
Average nuclear parton density	Event-by-event parton density fluctuations
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

Vector Meson (e.g., J/ψ) production in heavy nuclei

At Leading Order, 2-gluon exchange

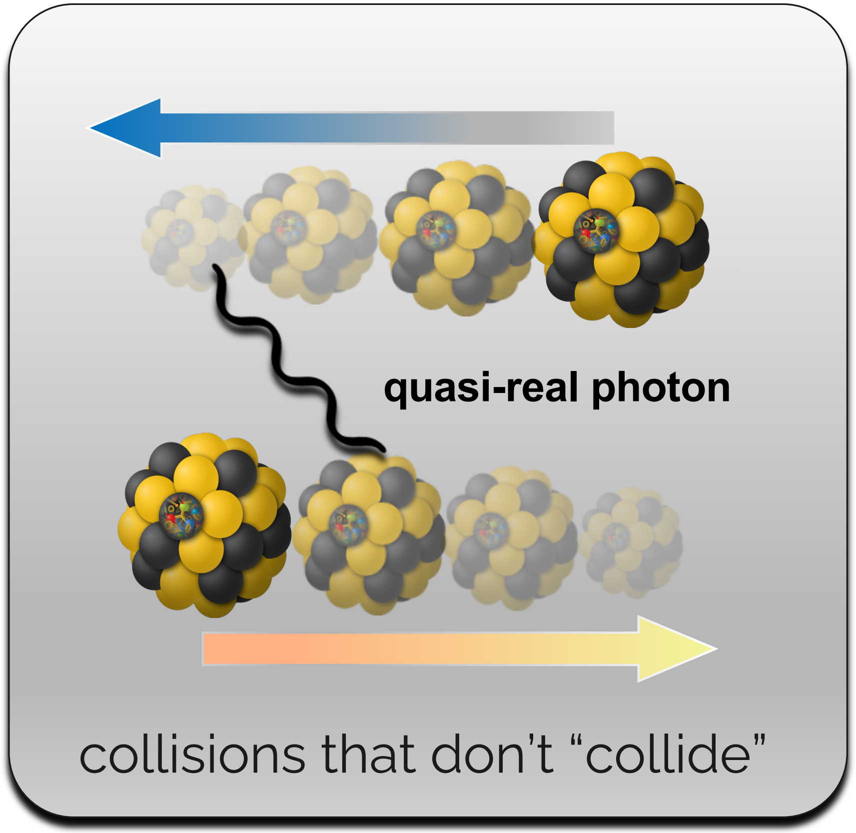


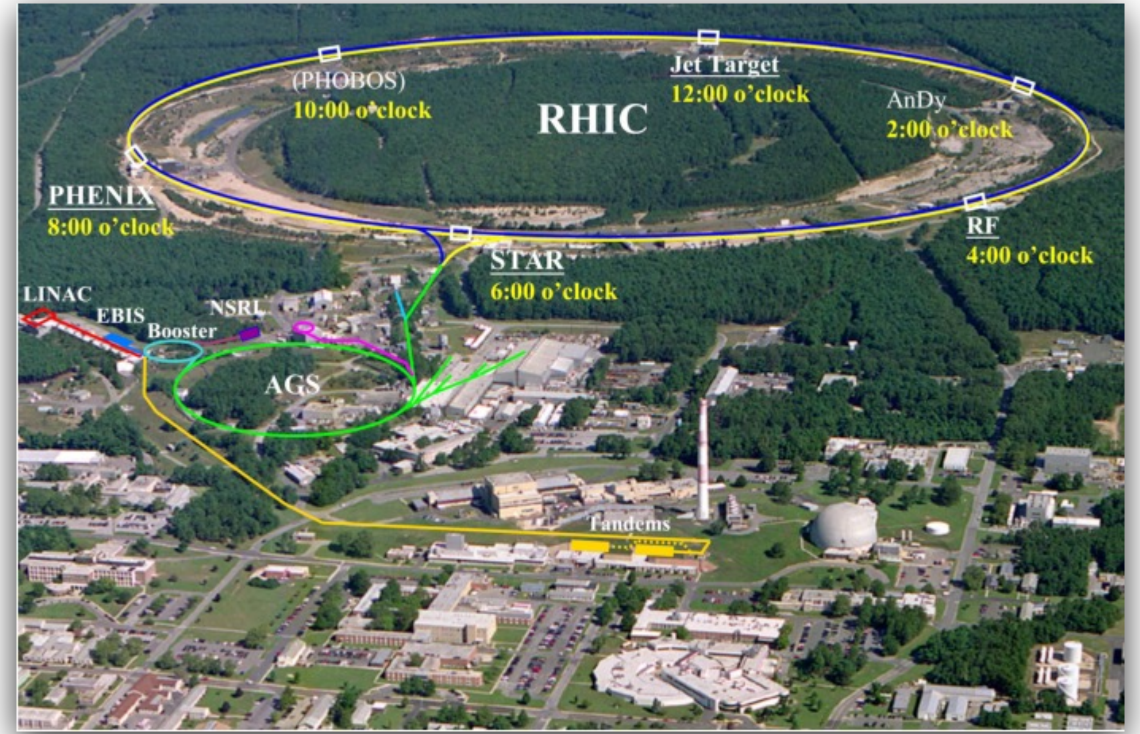
Coherent (target stays intact)	**Incoherent (target breaks up)**
Average nuclear parton density	Event-by-event parton density fluctuations
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

Three main physics goals:

1. Coherent production – **average** nuclear parton density
2. Incoherent production – **E-by-E fluctuations** of nuclear parton density
3. Imaging of nuclear parton **spatial** distribution in nuclei.

Ultra-Peripheral Collisions at RHIC



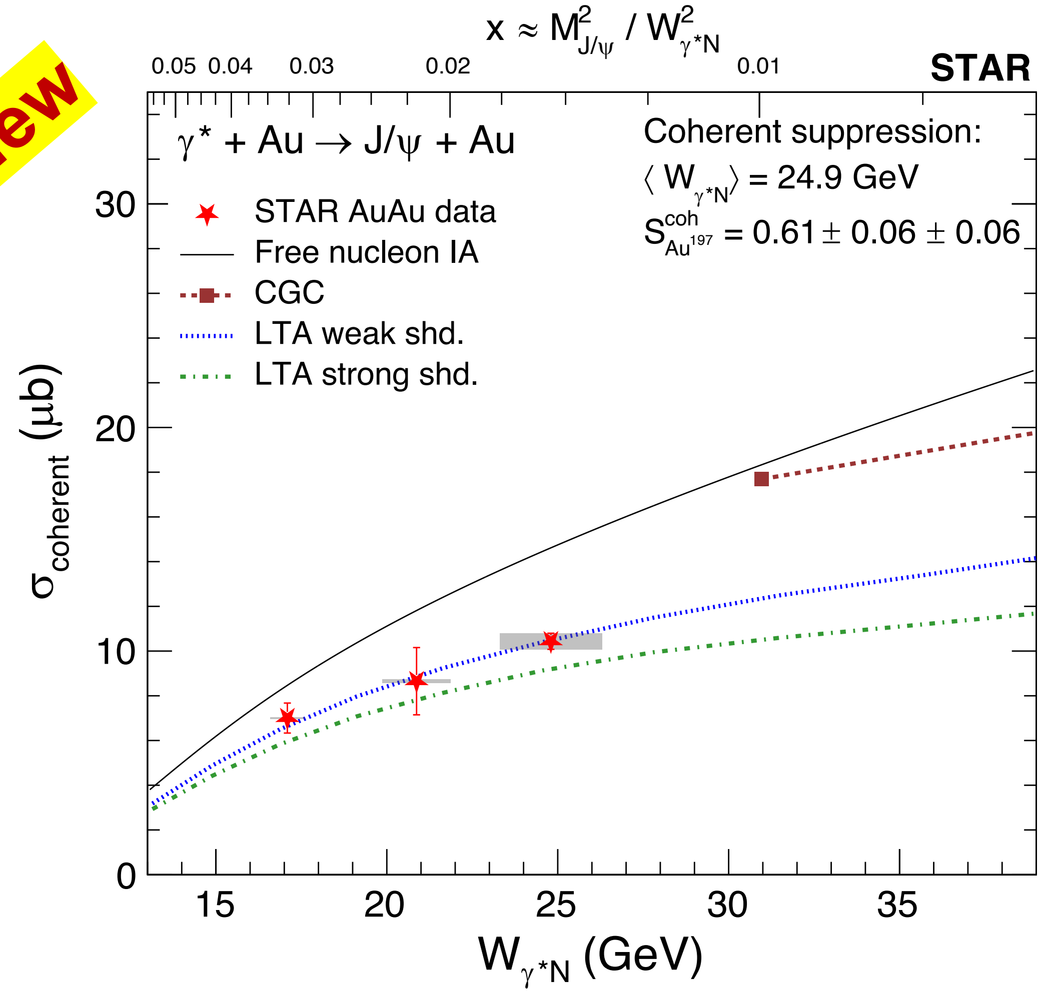


U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^{2} at 200 GeV and *pp* at 510 GeV

A versatile program with different species, energy, and polarization.

1. Coherent J/ψ photoproduction at RHIC

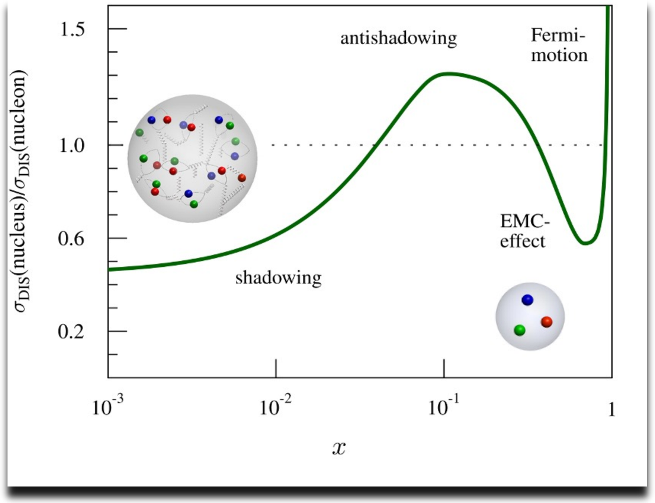
New



(submitted to PRC, arXiv:2311.13632)

What we learned:

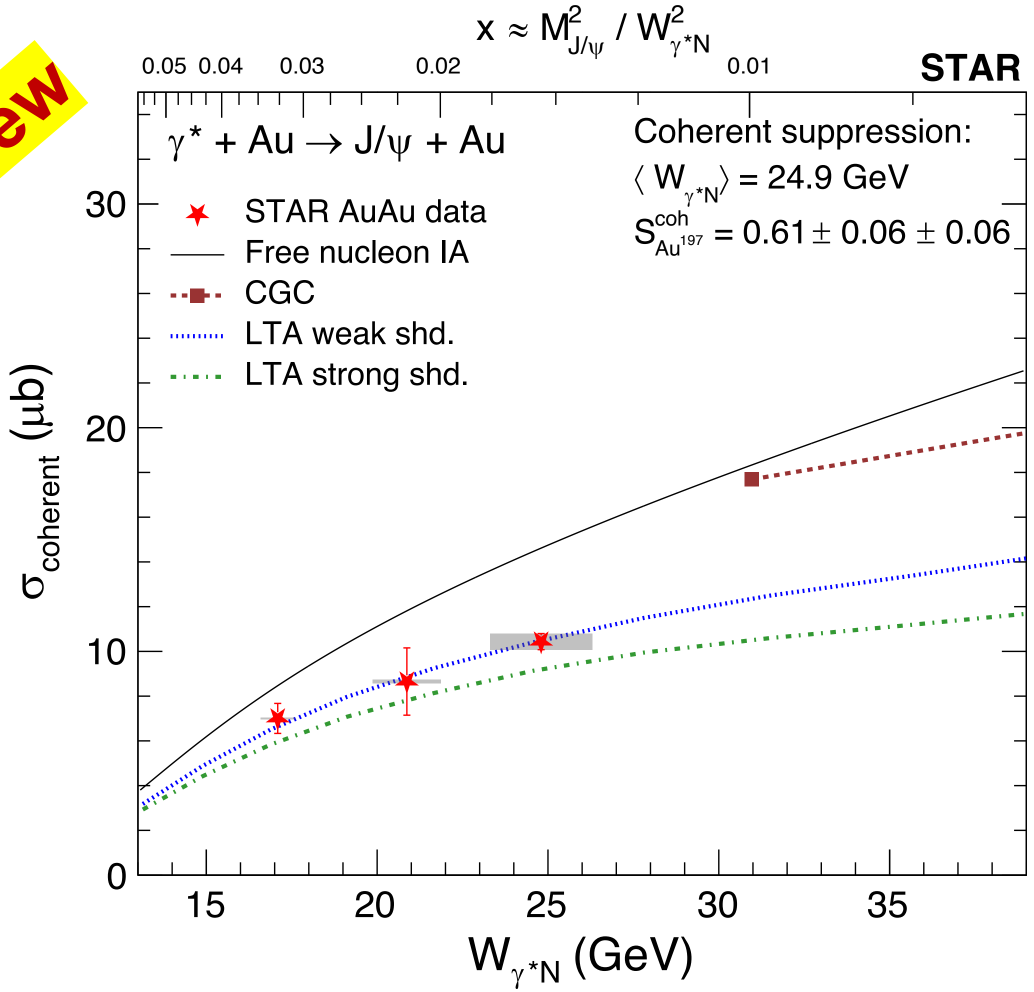
- Coherent J/ψ photoproduction cross section is suppressed even at x ~ 0.03-0.04.



Technical details of resolving photon energy ambiguity, data corrections, etc. See paper.

1. Coherent J/ψ photoproduction at RHIC

New



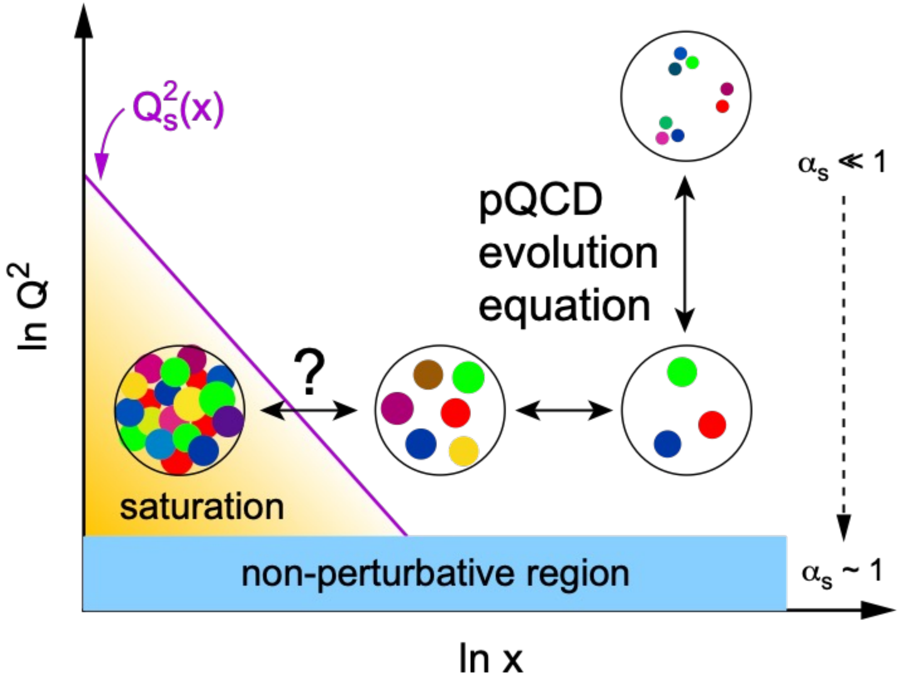
(submitted to PRC, arXiv:2311.13632)

What we learned:

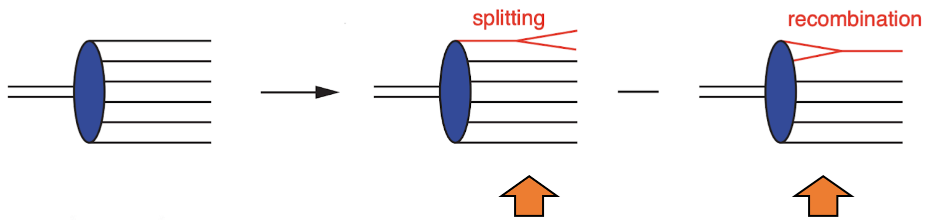
- Coherent J/ψ photoproduction cross section is suppressed even at x ~ 0.03-0.04.
- Gluon saturation model **(CGC)** cannot be applied and overpredicted at x ~ 0.01.
- **Leading twist shadowing** model works almost perfectly (tuning based on LHC data)

Technical details of resolving photon energy ambiguity, data corrections, etc. See paper.

Digression:
– what is saturation and what is Leading twist shadowing?



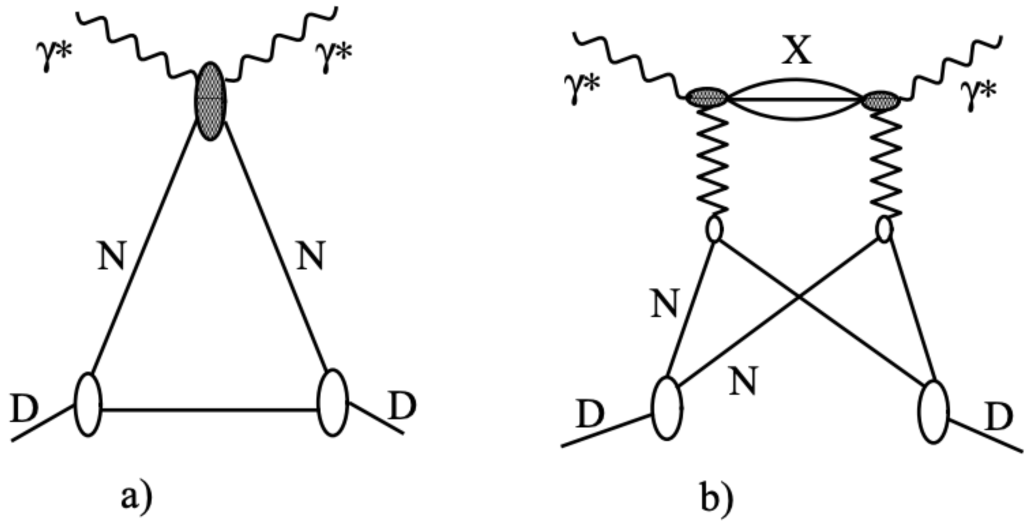
Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s



$$\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x,r_T) - \alpha_s [N(x,r_T)]^2$$

This quadratic term is why we call it the nonlinear QCD effect

Digression:
– what is saturation and what is Leading twist shadowing?

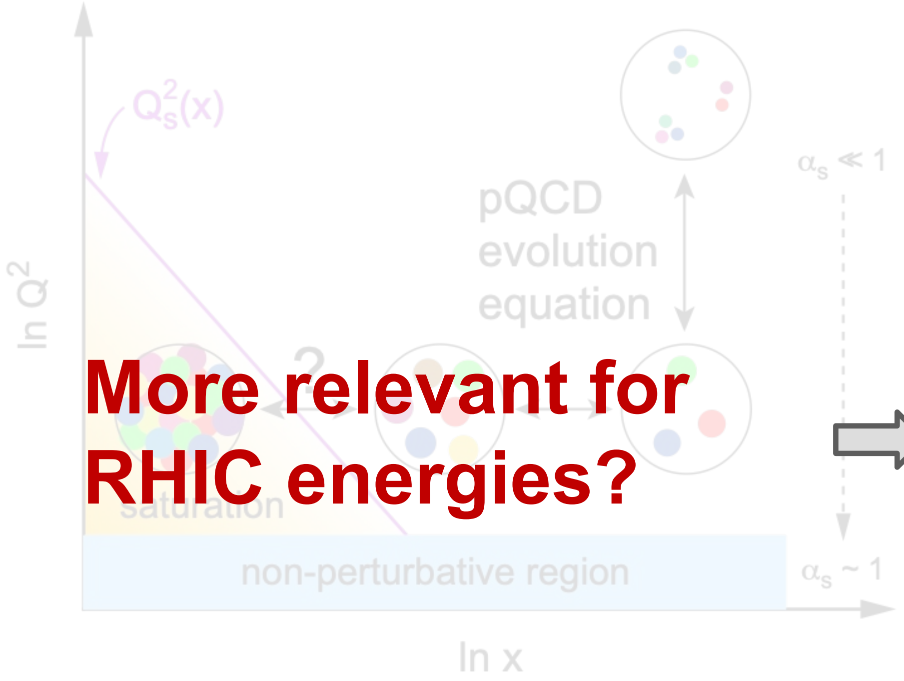


L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s

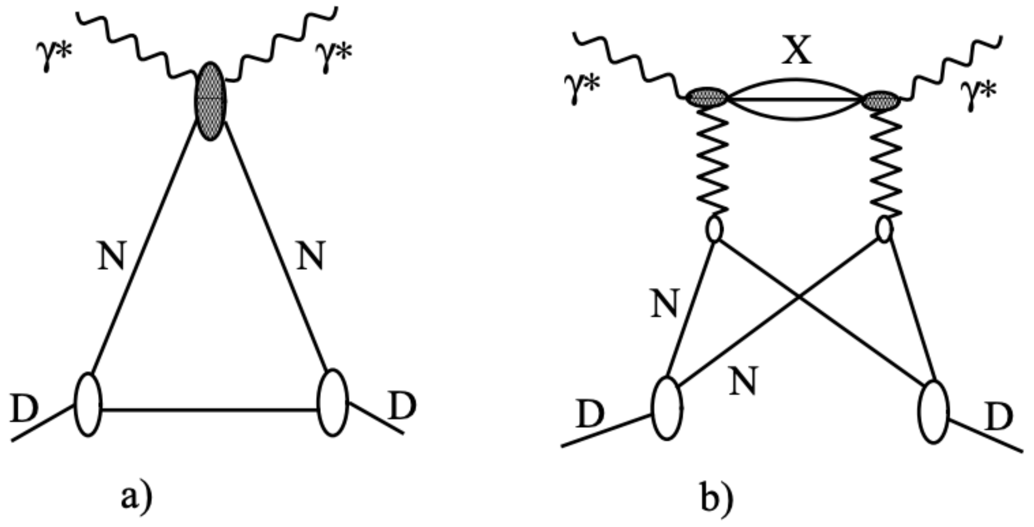
Leading Twist Approximation (LTA)
Combination of Gribov-Glauber theory, QCD factorization, and HERA diffractive data

Digression:
– what is saturation and what is Leading twist shadowing?



More relevant for RHIC energies?

Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s

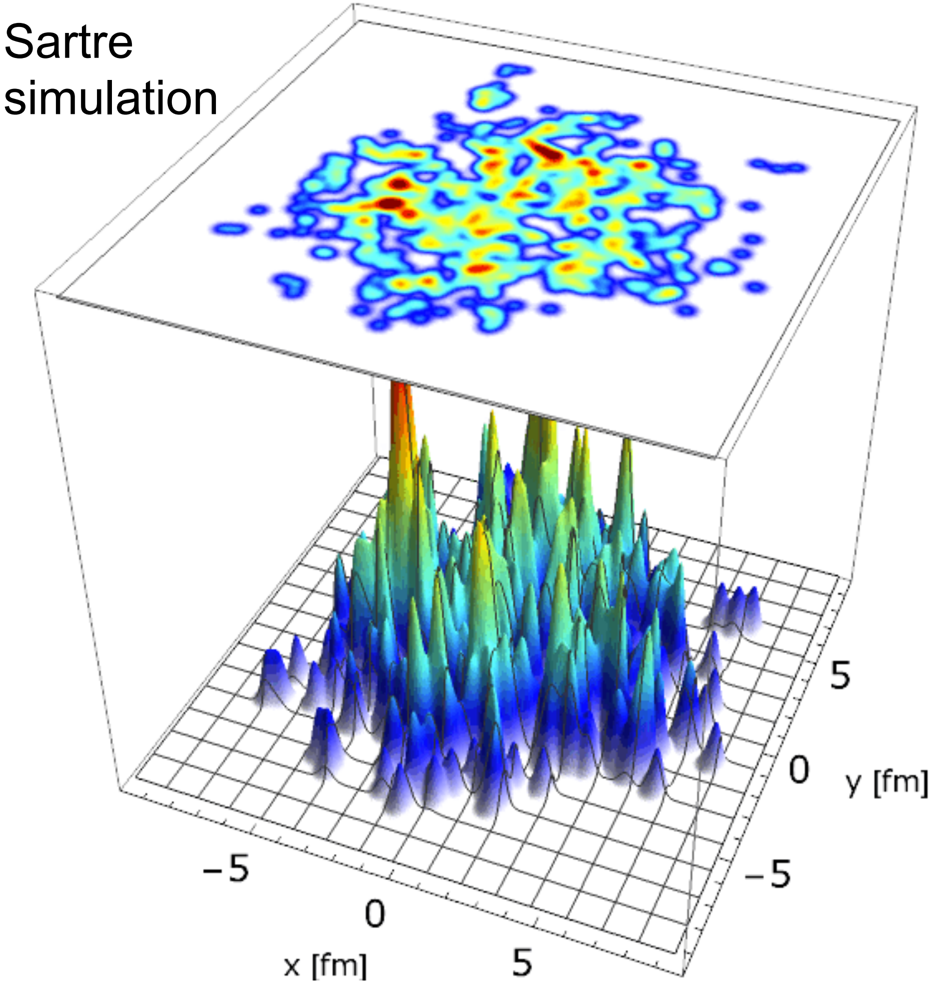


L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

Leading Twist Approximation (LTA)
Combination of Gribov-Glauber theory, QCD factorization, and HERA diffractive data

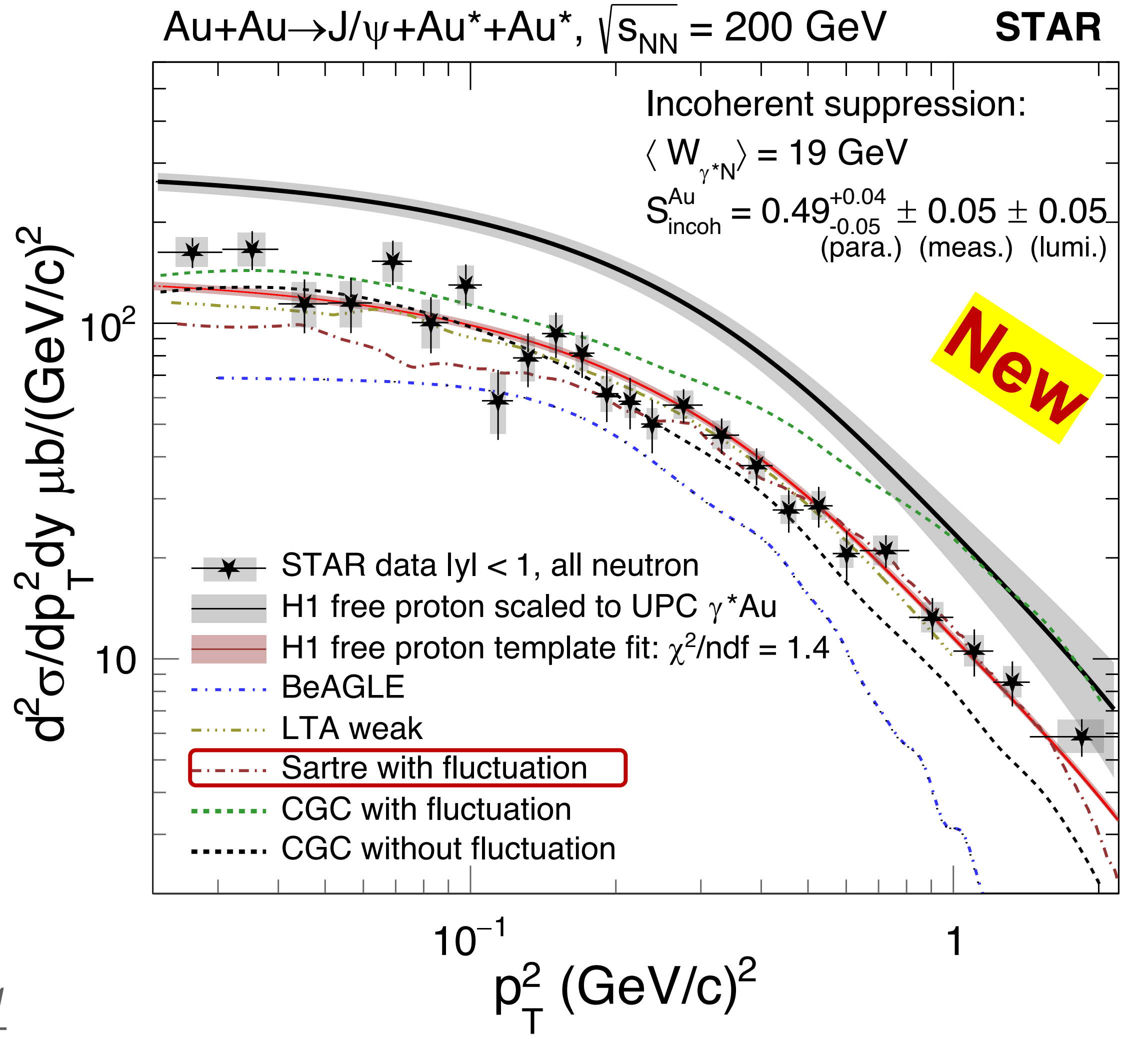
2. Incoherent J/ψ photoproduction at RHIC

Sartre simulation



[made by A. Kumar (IIT, Delhi)]

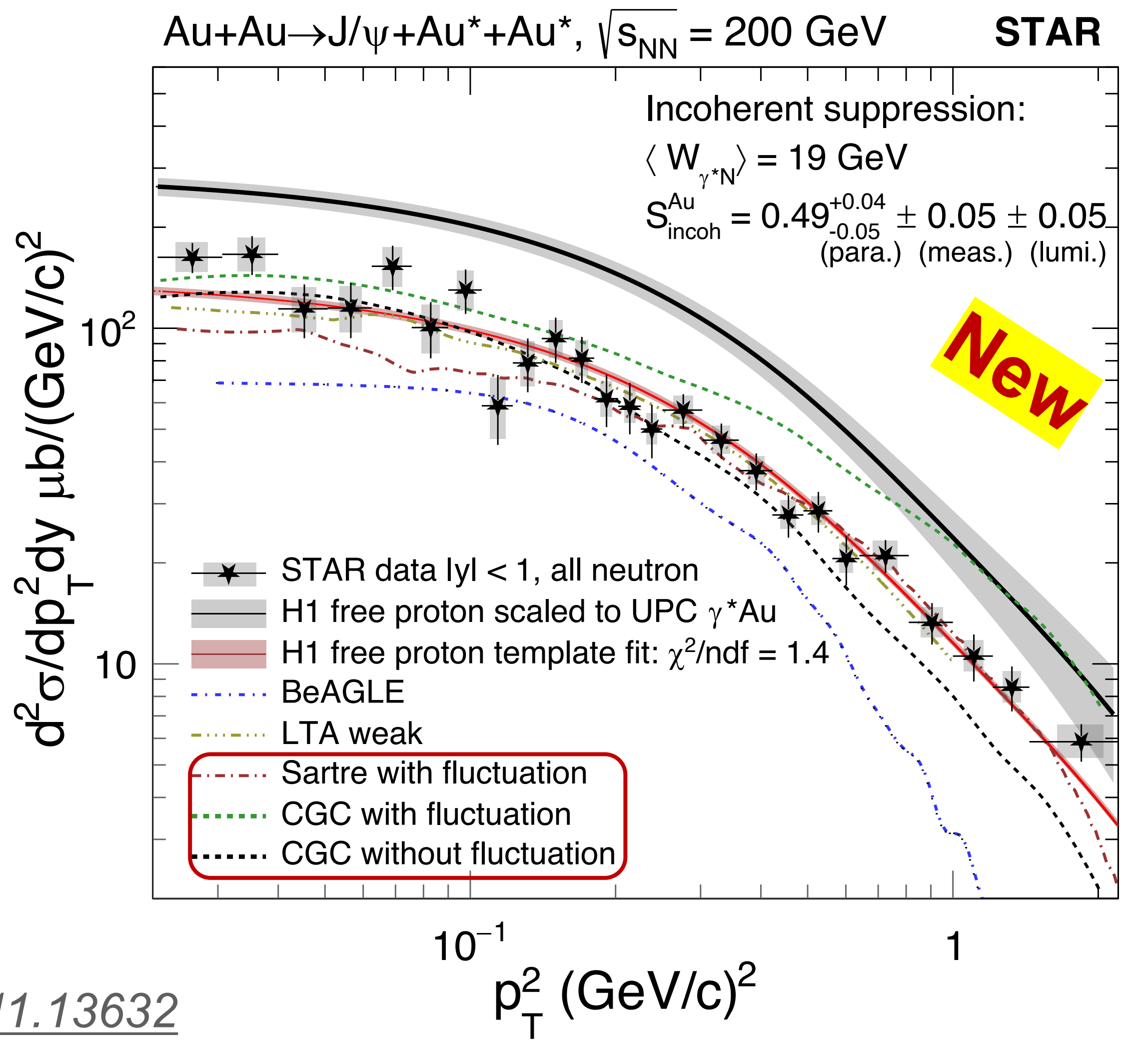
arXiv:231



2. Incoherent J/ψ photoproduction at RHIC

What we learned:

- CGC with and without fluctuation of gluon density are compared (shape only), while **none can describe the data.**

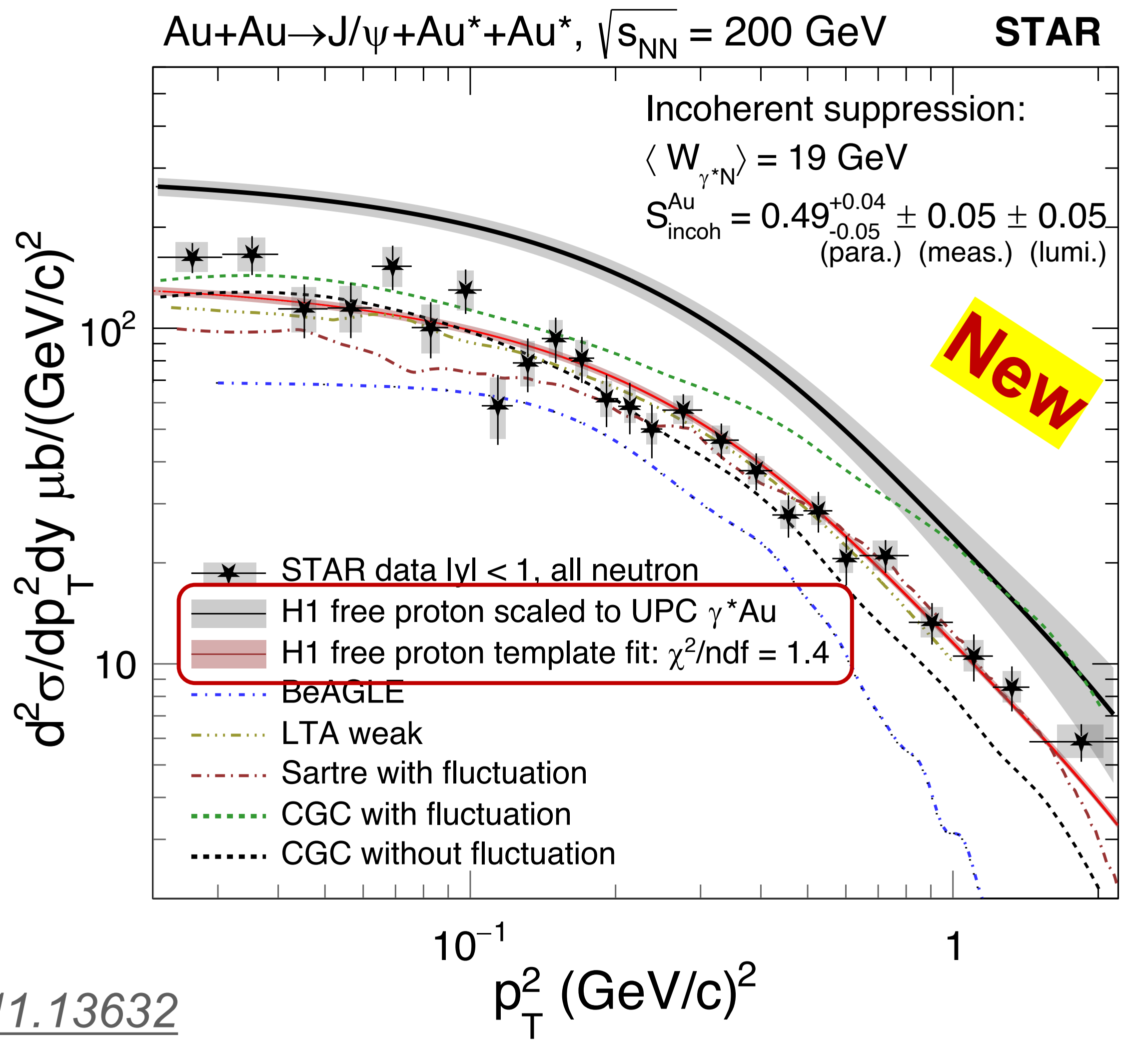


arXiv:2311.13632

2. Incoherent J/ψ photoproduction at RHIC

What we learned:

- CGC with and without fluctuation of gluon density are compared (shape only), while **none can describe the data.**
- The shape of the p_T^2 is consistent with free proton. **No additional `fluctuation`.**

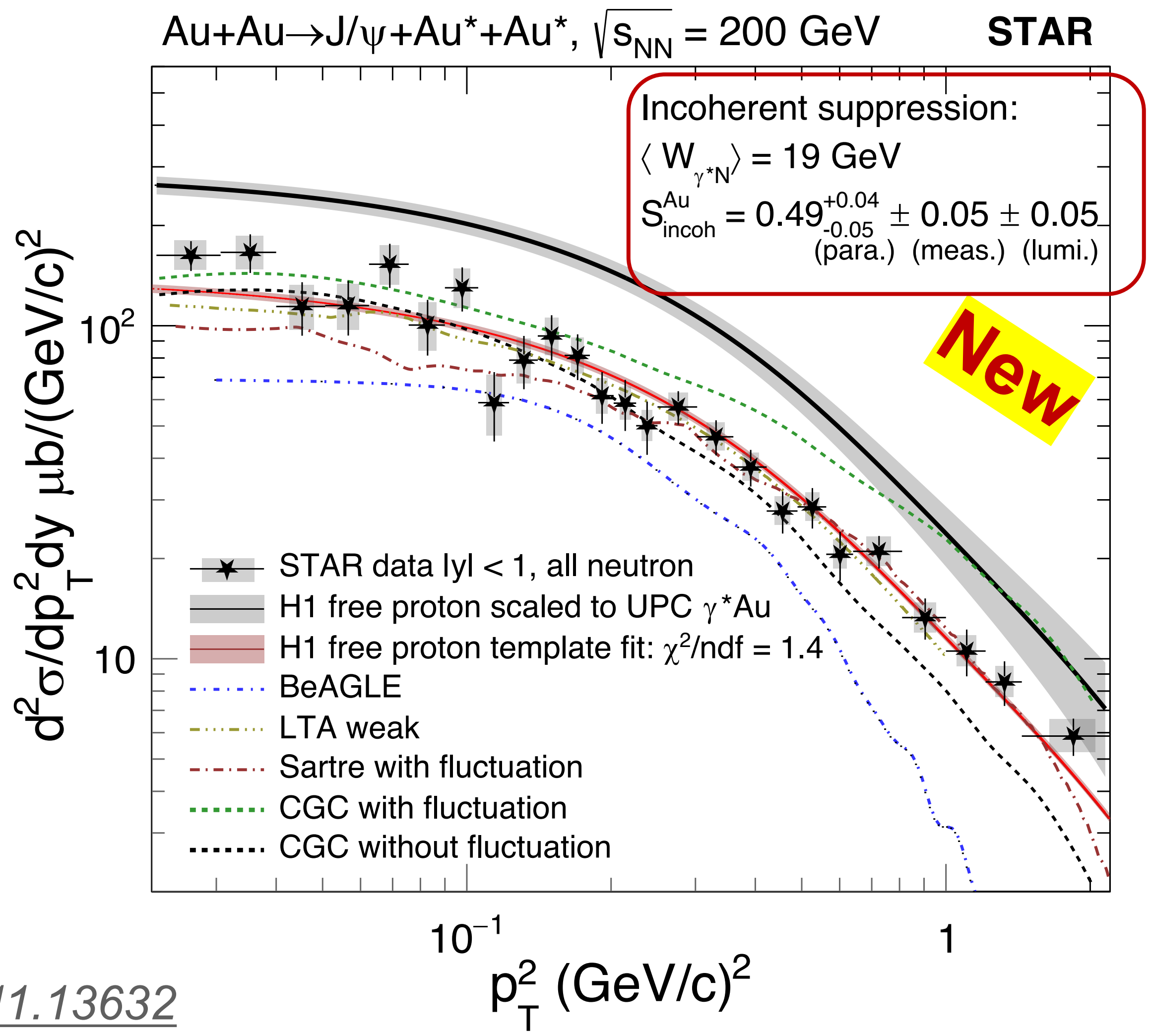


arXiv:2311.13632

2. Incoherent J/ψ photoproduction at RHIC

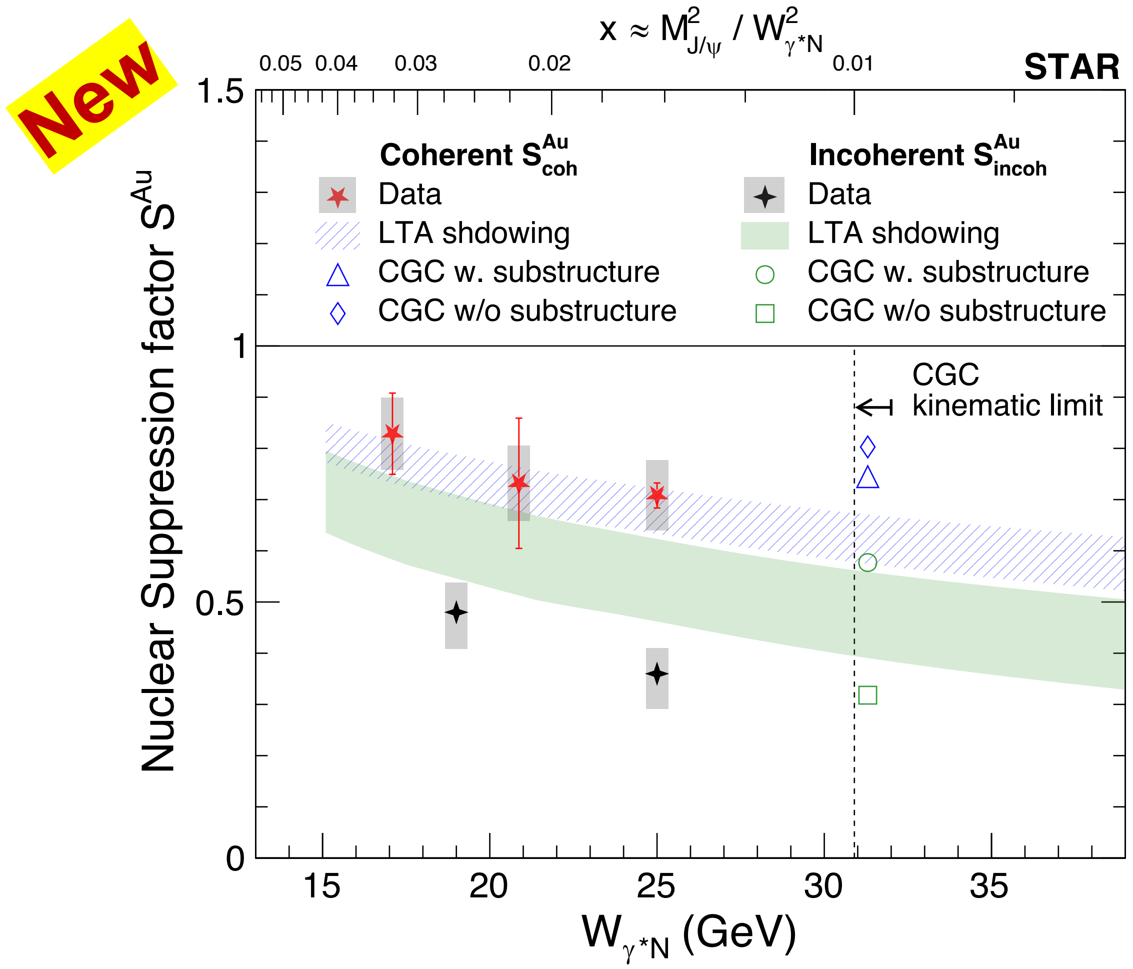
What we learned:

- CGC with and without fluctuation of gluon density are compared (shape only), while **none can describe the data.**
- The shape of the p_T^2 is consistent with free proton. **No additional \`fluctuation\`.**
- Incoherent cross section is also suppressed w.r.t free proton, and stronger than coherent!



arXiv:2311.13632

Nuclear suppression factor

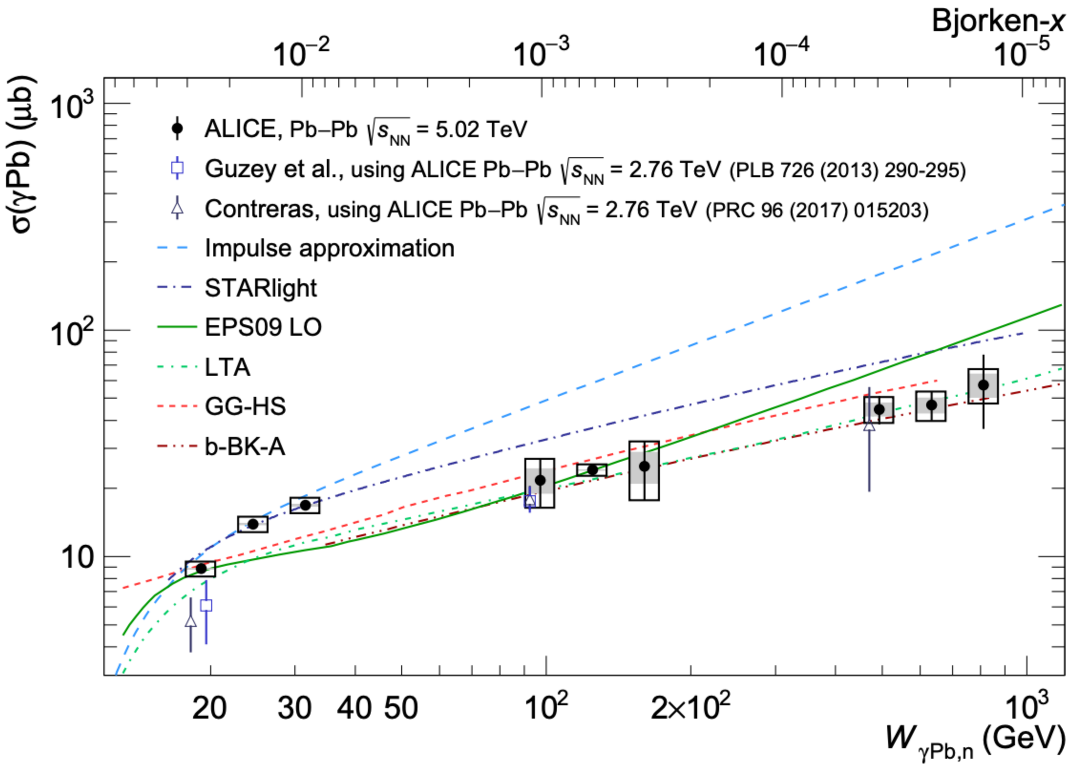


What we learned:

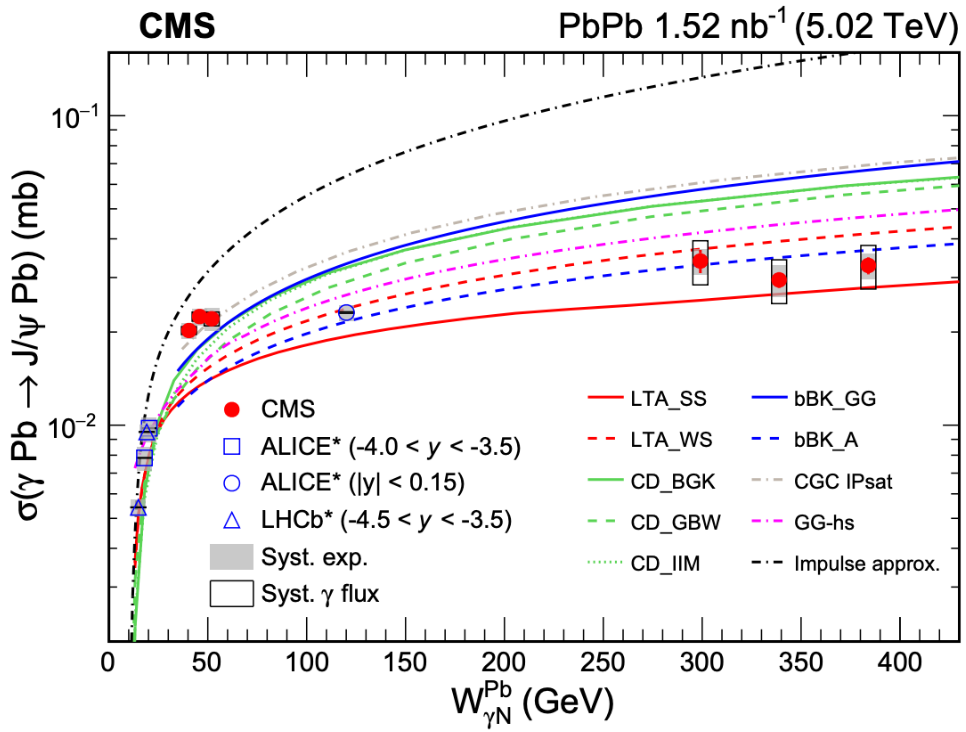
- Significant suppression of both coherent and incoherent J/ψ photoproduction.
- Incoherent is **twice as suppressed** as that of coherent. Even **stronger than the "strong" shadowing mode** in Leading twist shadowing model.
- Another observable to **disfavor** fluctuation model.

(submitted to PRL, arXiv:2311.13637)

CGC describes better at higher energies?



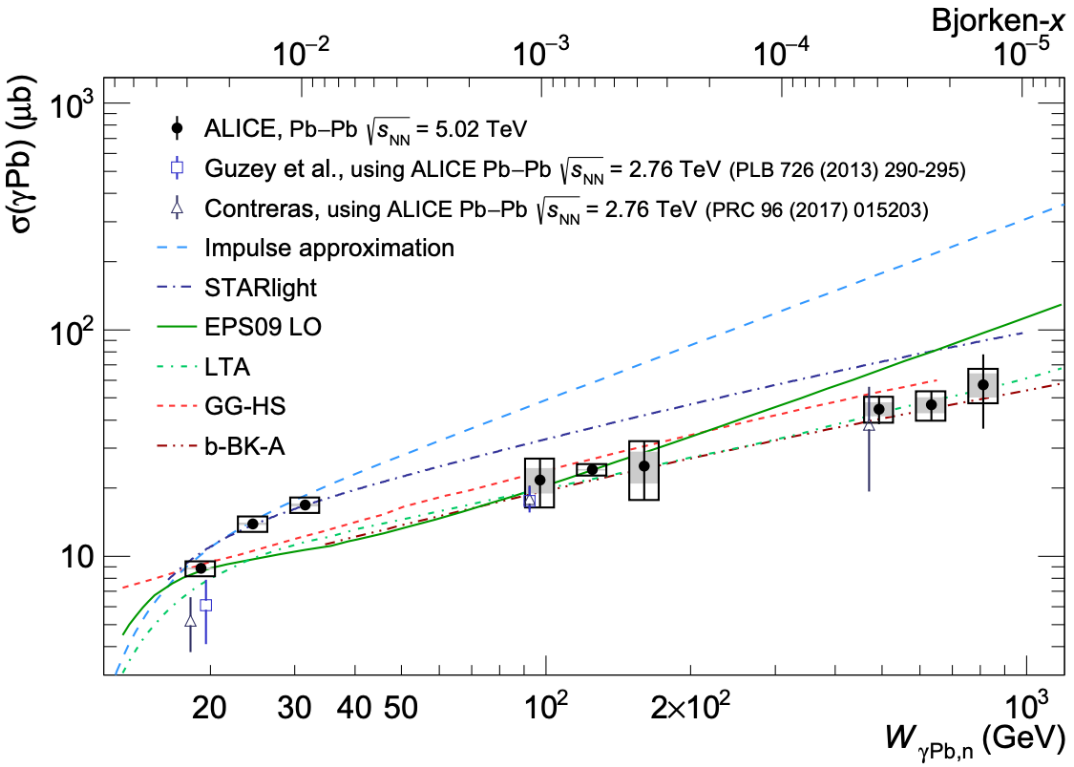
JHEP 10 (2023) 119



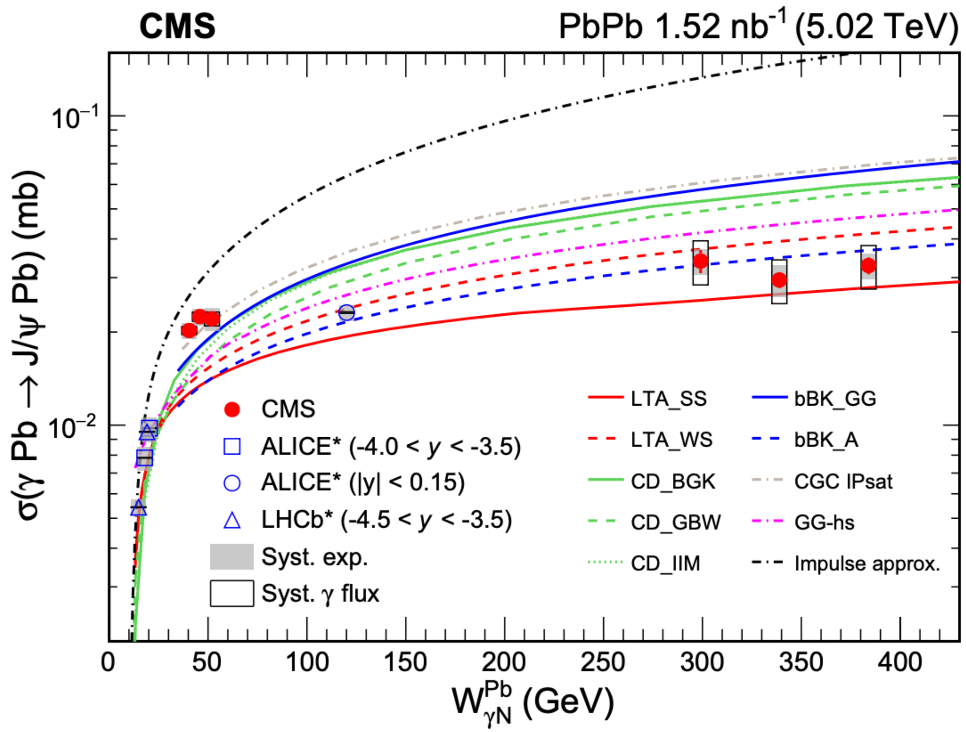
Phys. Rev. Lett. 131 (2023) 262301

- Yes, but LTA describes the data equally well.
- None of these models can describe the entire energy dependence and **all models generally reach a “similar conclusion”.**

CGC describes better at higher energies?



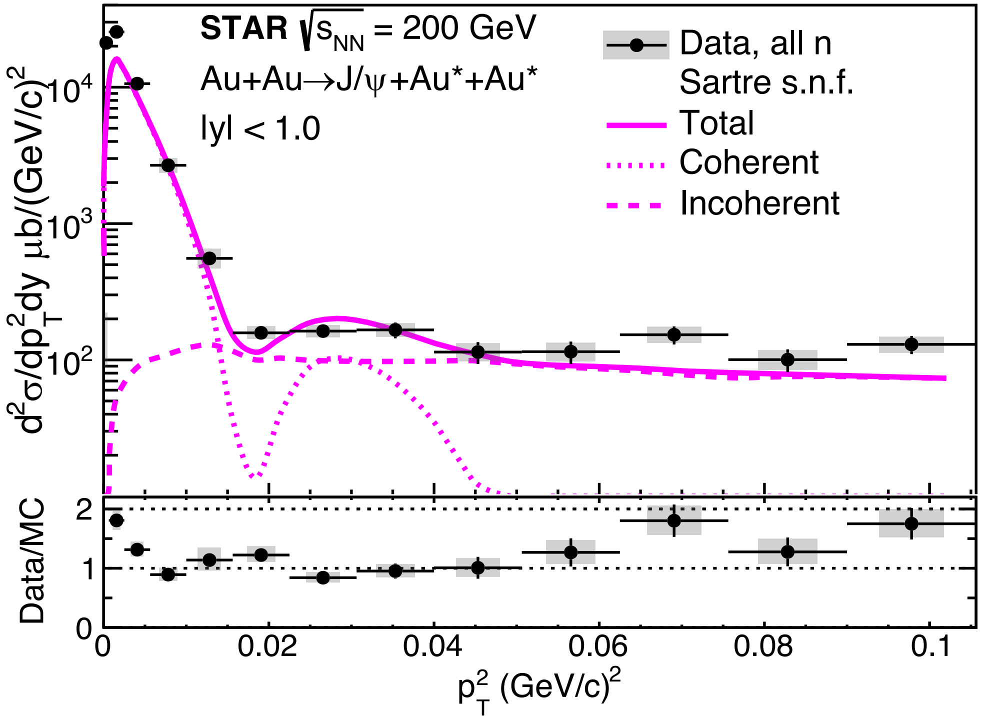
JHEP 10 (2023) 119



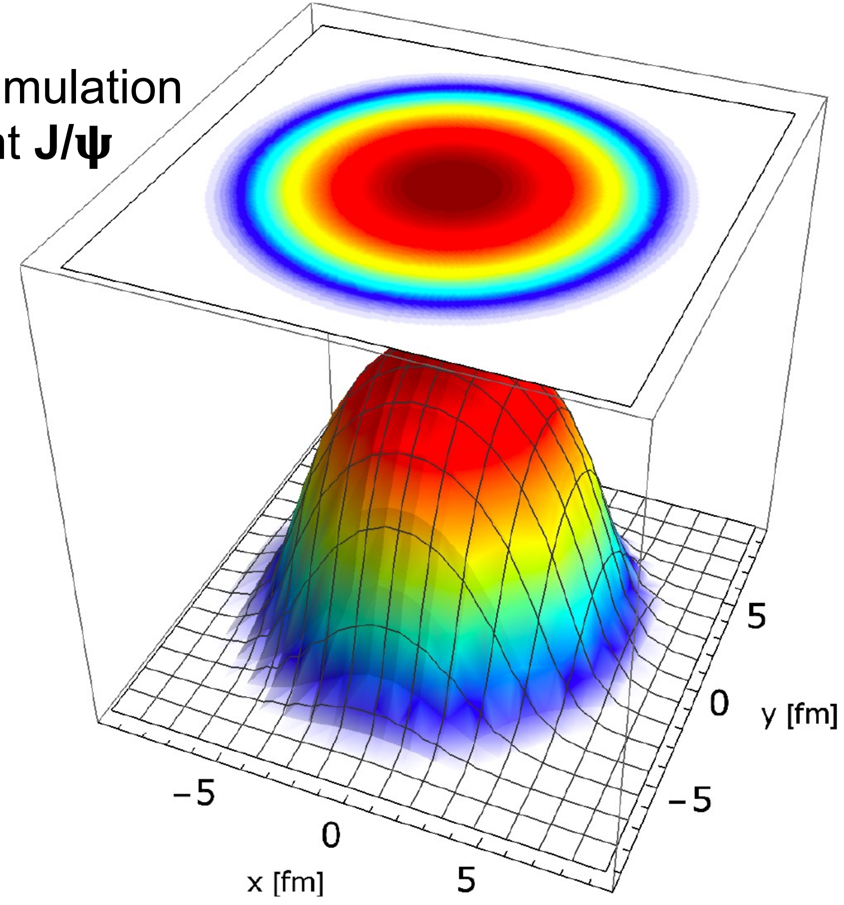
Phys. Rev. Lett. 131 (2023) 262301

Separating the two models is one of the most pressing questions in UPC Vector Meson physics

3. Imaging the parton spatial distribution



Sartre simulation
Coherent **J/ψ**



[made by A. Kumar (IIT, Delhi)]

Overwhelming incoherent at higher p_T^2 →
cannot constrain the gluon spatial distribution

What's next?

Two questions:

a) Separating CGC vs LTA at low-x or LHC energies
b) Separating Coherent and Incoherent as a function of p_T^2

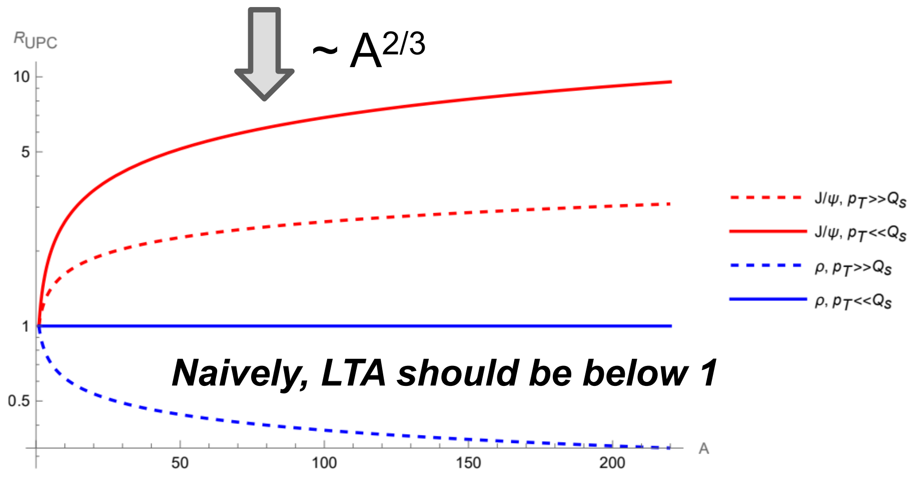
a) Separating CGC vs LTA at low-x or LHC energies

New proposal

- Diffractive Vector Meson over inclusive jet/hadron photoproduction in UPCs

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\mathrm{A+A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\mathrm{p+A}}}.$$

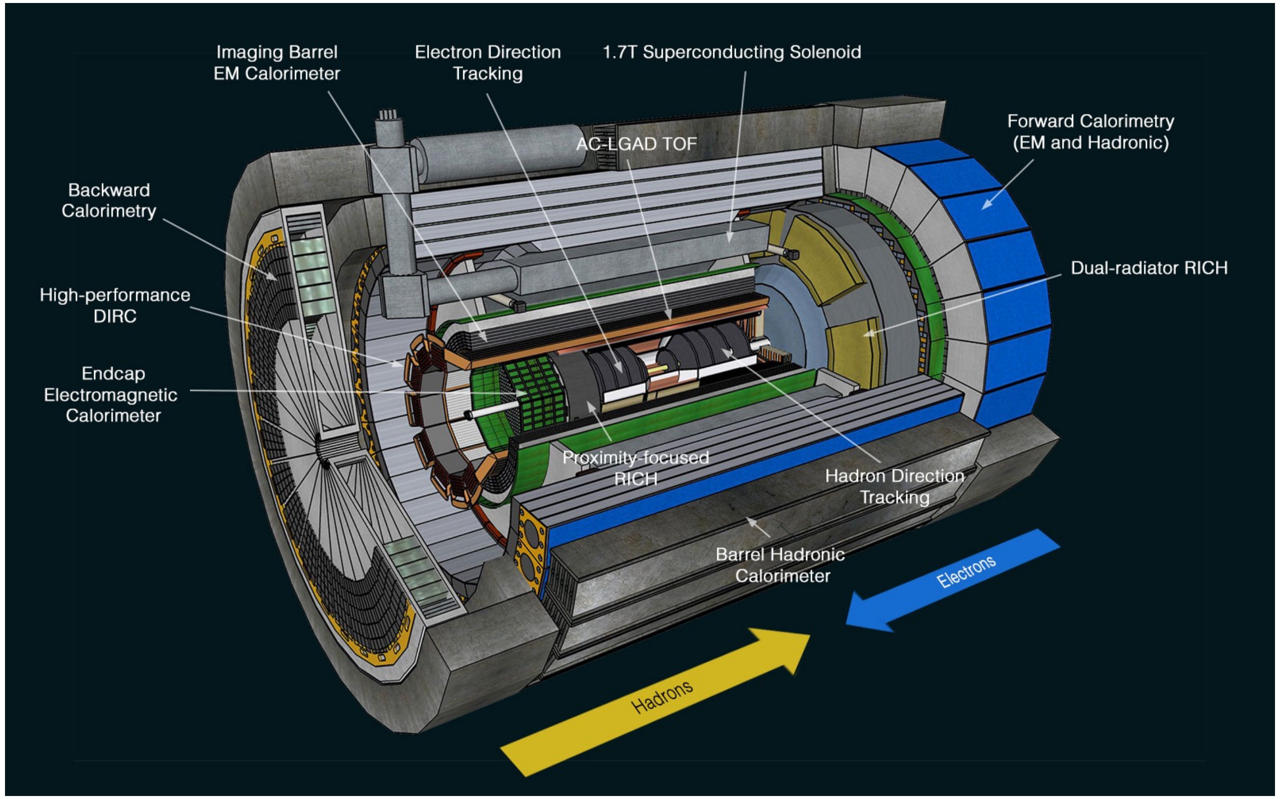
Unambiguous signal of saturation from **J/ψ**



New

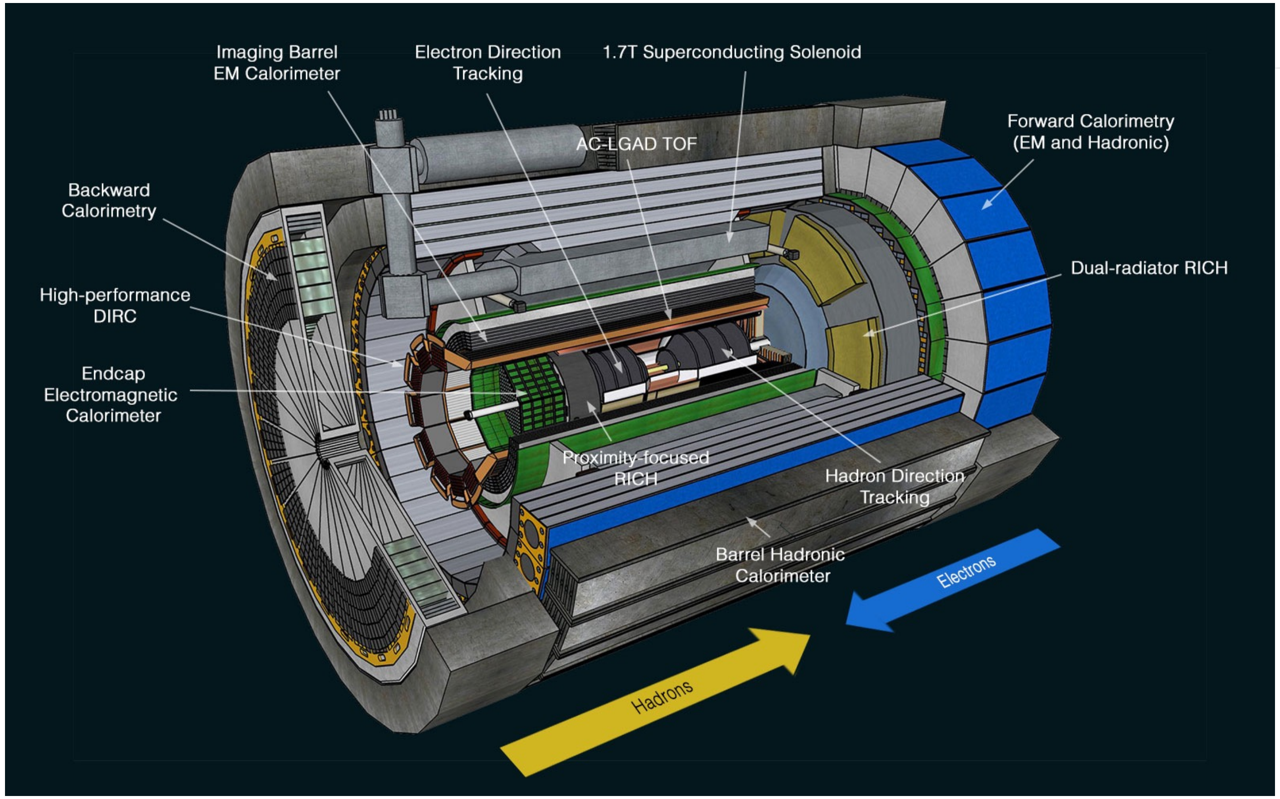
*Y. Kovchegov, H. Sun, **ZT** (2023), arXiv:2311.12208, submitted to PRD*

b) Separating Coherent and Incoherent as a function of p_T^2

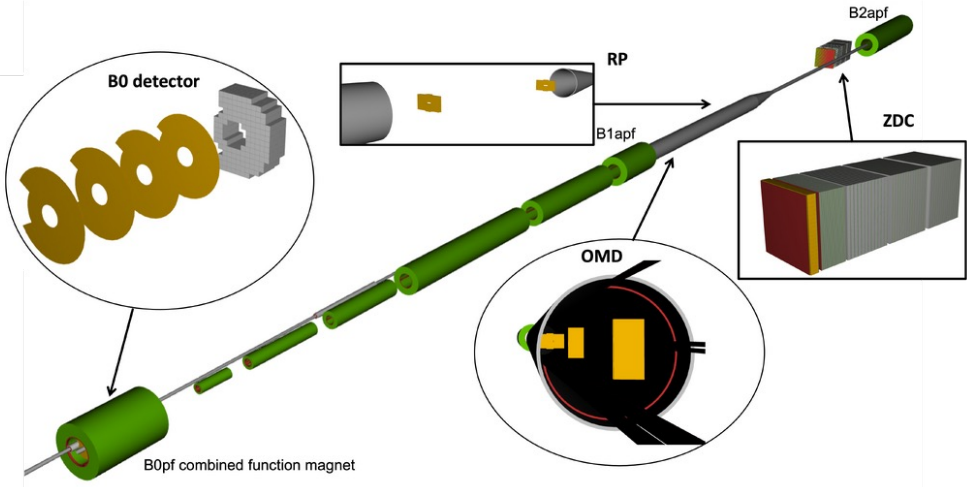


The ePIC detector – at the Electron-Ion Collider

b) Separating Coherent and Incoherent as a function of p_T^2



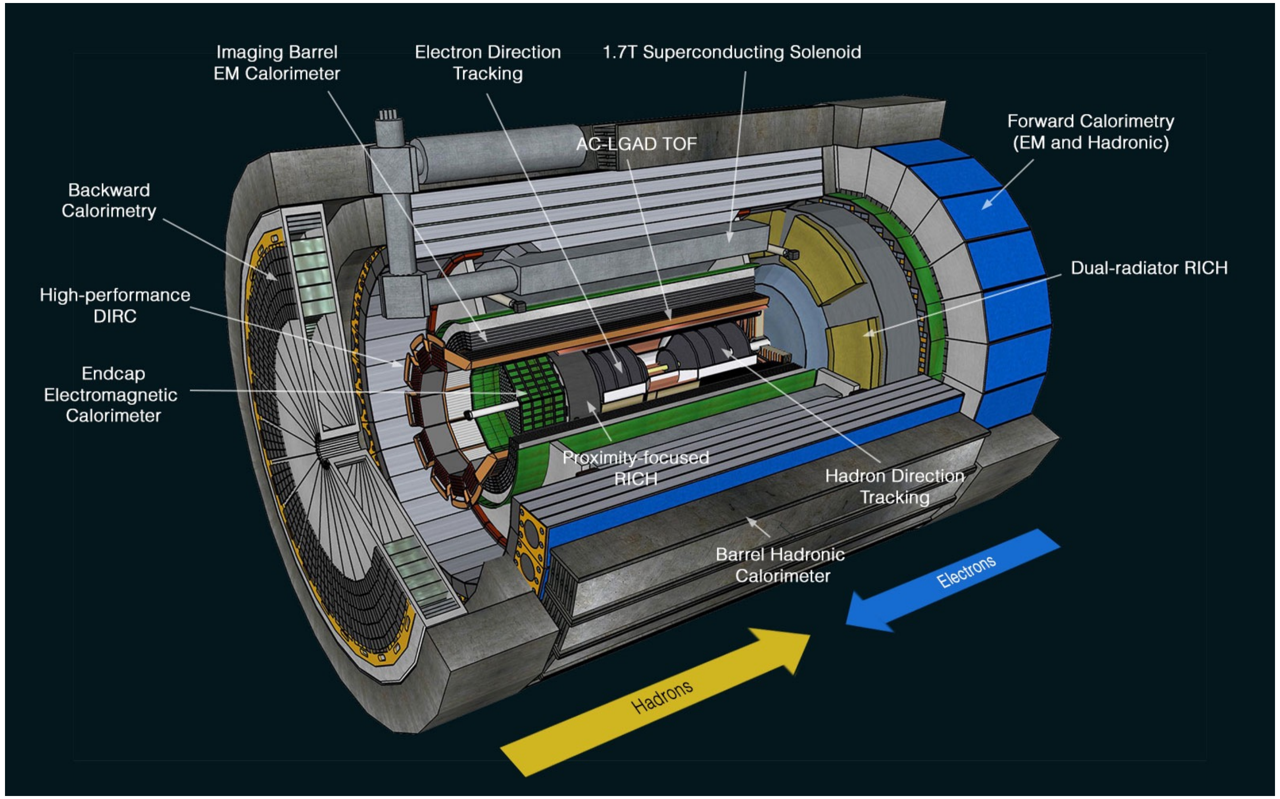
The ePIC detector – at the Electron-Ion Collider

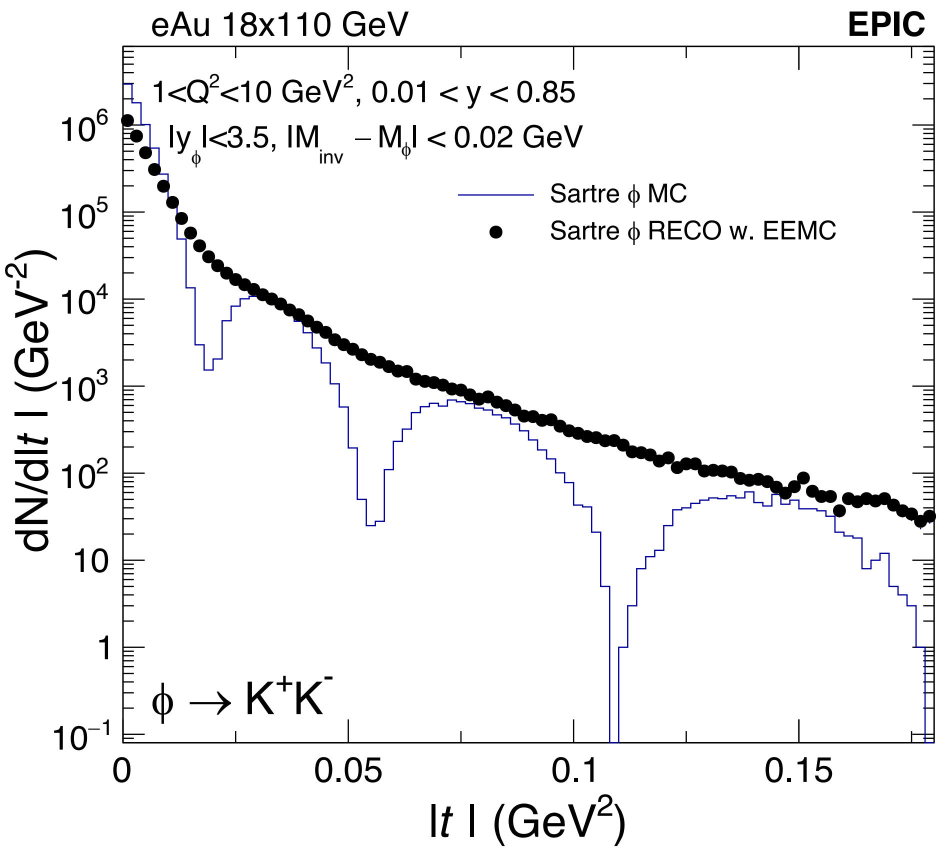


Far-forward detector system: What we use to select/veto the incoherent production

b) Separating Coherent and Incoherent as a function of p_T^2

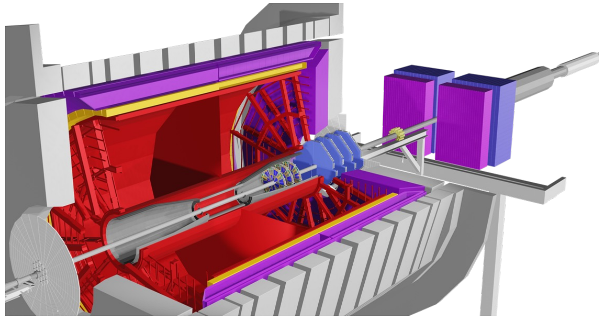
Simulation Campaign Dec 2023





The ePIC detector – at the Electron-Ion Collider *It's still challenging to measure the gluon spatial distribution*

Future opportunities



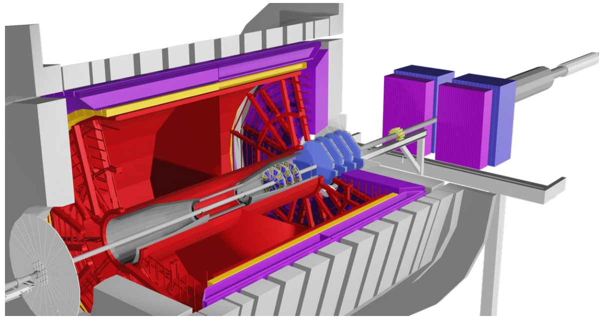
Since 2022, STAR has forward detectors (**2.5 < η < 4.0**):

- J/ψ coherent and incoherent production with **high precision**. Lower W towards a few GeV, and high t to better understand fluctuation.
- ***ϕ* photoproduction.**
- **Photoproduction of jets.**
- **New observables.**

RHIC 23-25

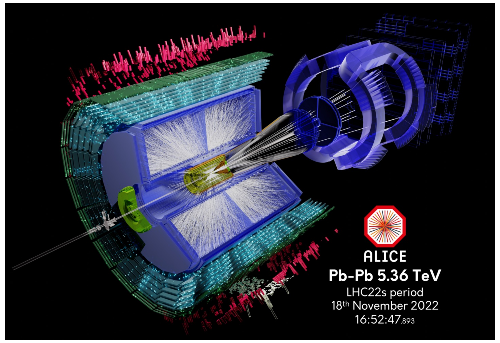
2023 2025 2029 2034+

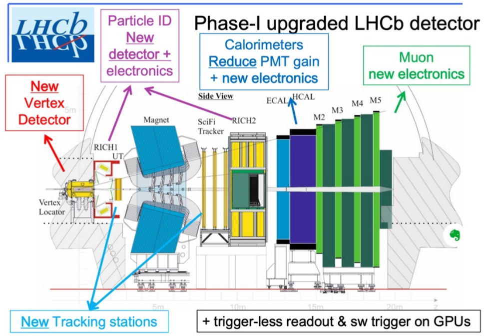
Future opportunities

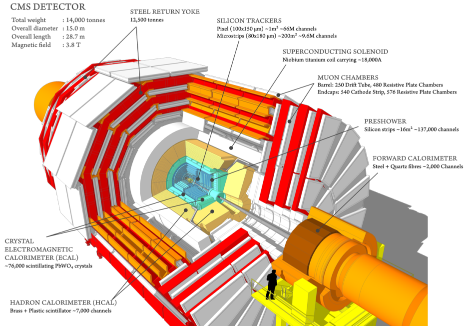


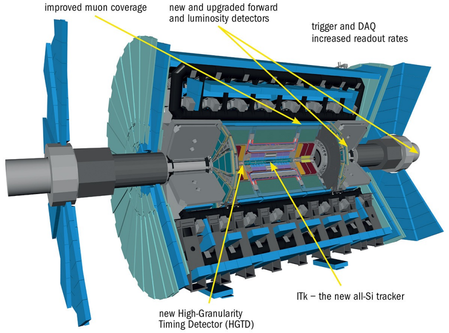
Since 2022, STAR has forward detectors (**2.5 < η < 4.0**):

- J/ψ coherent and incoherent production with **high precision**. Lower W towards a few GeV, and high t to better understand fluctuation.
- **ϕ photoproduction.**
- **Photoproduction of jets.**
- **New observables.**







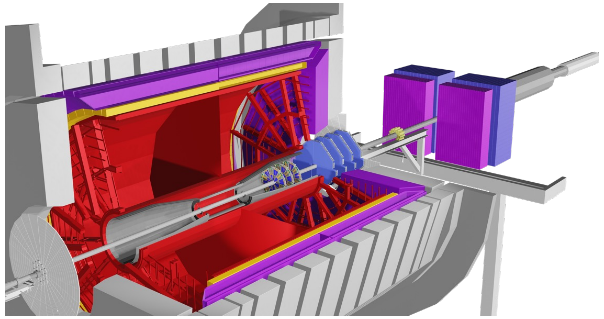


All LHC experiments will have significant upgrades in Run 3 & 4 (e.g., wide acceptances, ALICE FoCal, etc.). **Lower-x reach!**

RHIC 23-25 & LHC Run 3 — LHC Run 4

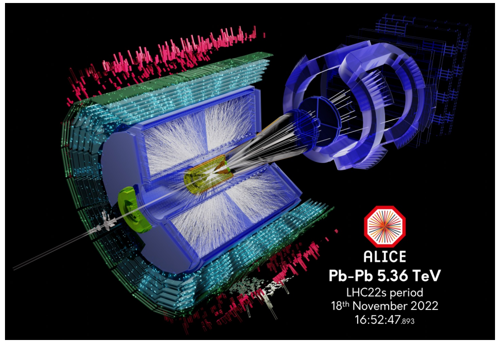
2023 — 2025 — 2029 — 2034+

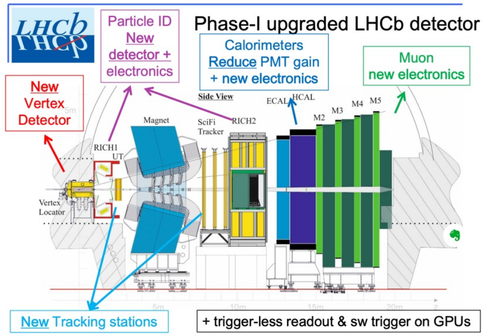
Future opportunities

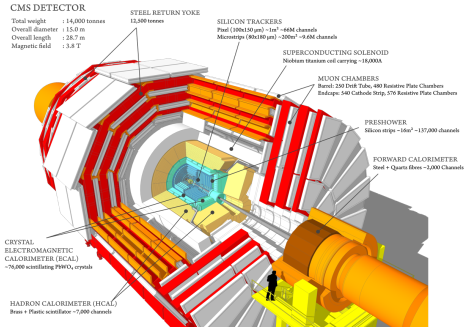


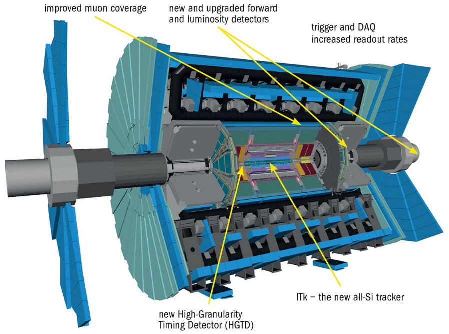
Since 2022, STAR has forward detectors (**2.5 < η < 4.0**):

- J/ψ coherent and incoherent production with **high precision**. Lower W towards a few GeV, and high t to better understand fluctuation.
- ***ϕ* photoproduction.**
- **Photoproduction of jets.**
- **New observables.**





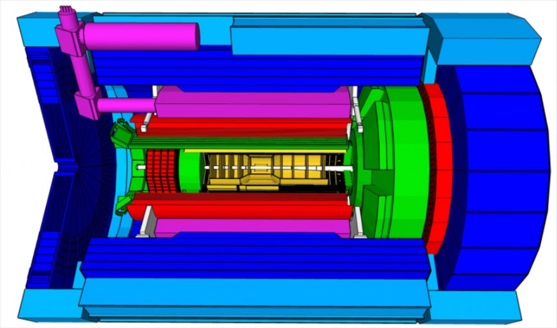




All LHC experiments will have significant upgrades in Run 3 & 4 (e.g., wide acceptances, ALICE FoCal, etc.). **Lower-x reach!**

EIC era

The ePIC detector and possible a 2nd detector: the ultimate machine for understanding saturation quantitatively with a wide variety of observables.



RHIC 23-25 & LHC Run 3 — LHC Run 4

2023 2025 2029 2034+

Summary

- Diffractive Vector-Meson production is a powerful probe for understanding the cold QCD physics in nuclei.
  - *Large nuclear suppression of* **J/ψ *photoproduction***.
  - *Leading Twist Shadowing describes better the RHIC data, while for the LHC we need new observables to differentiate models.*

- RHIC and LHC UPC data are complimentary, together spans a wide range of energy and kinematic phase space.

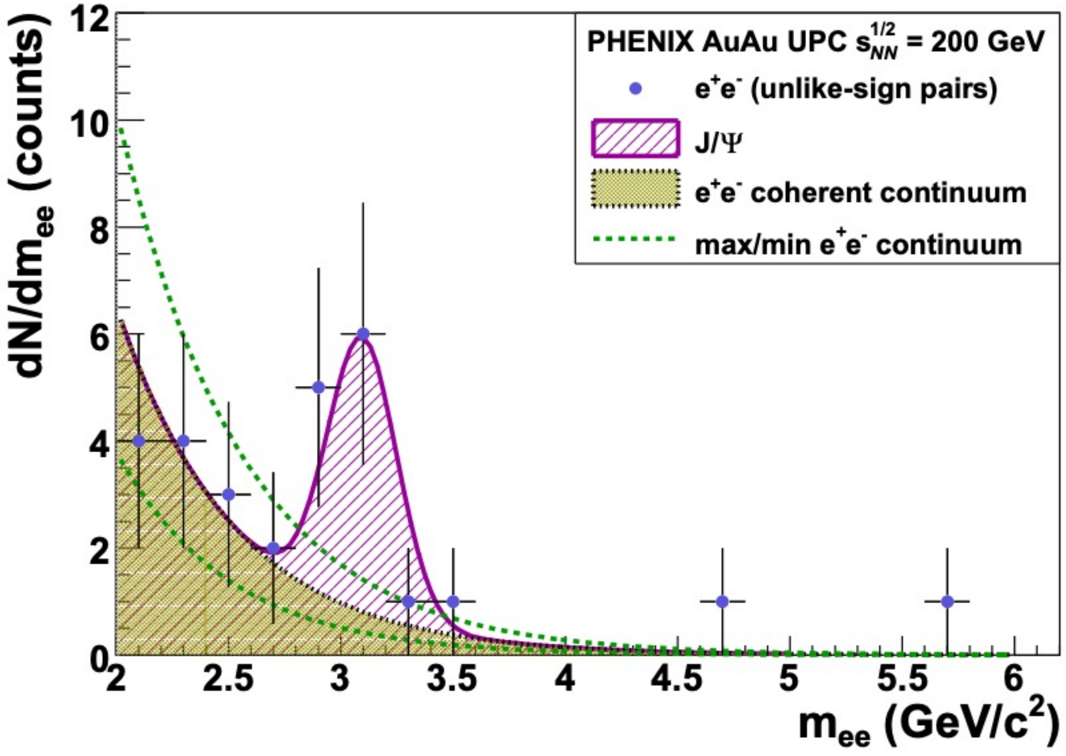
Energy frontier: UPCs at RHIC and the LHC can help understand the nuclear parton modification at low-x.

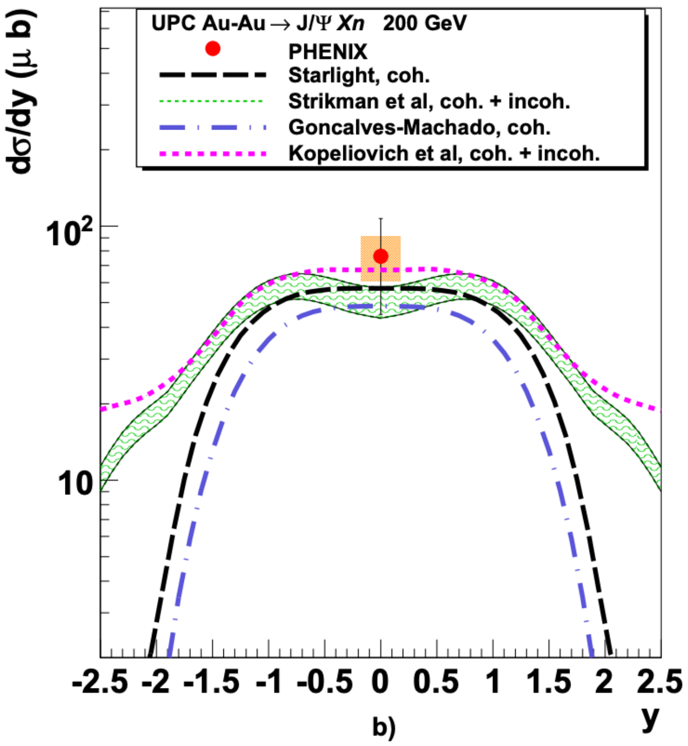
Precision frontier: EIC will be the ultimate machine to understand the detail of nuclear dynamics in 3D.

Backup

Early RHIC data from PHENIX

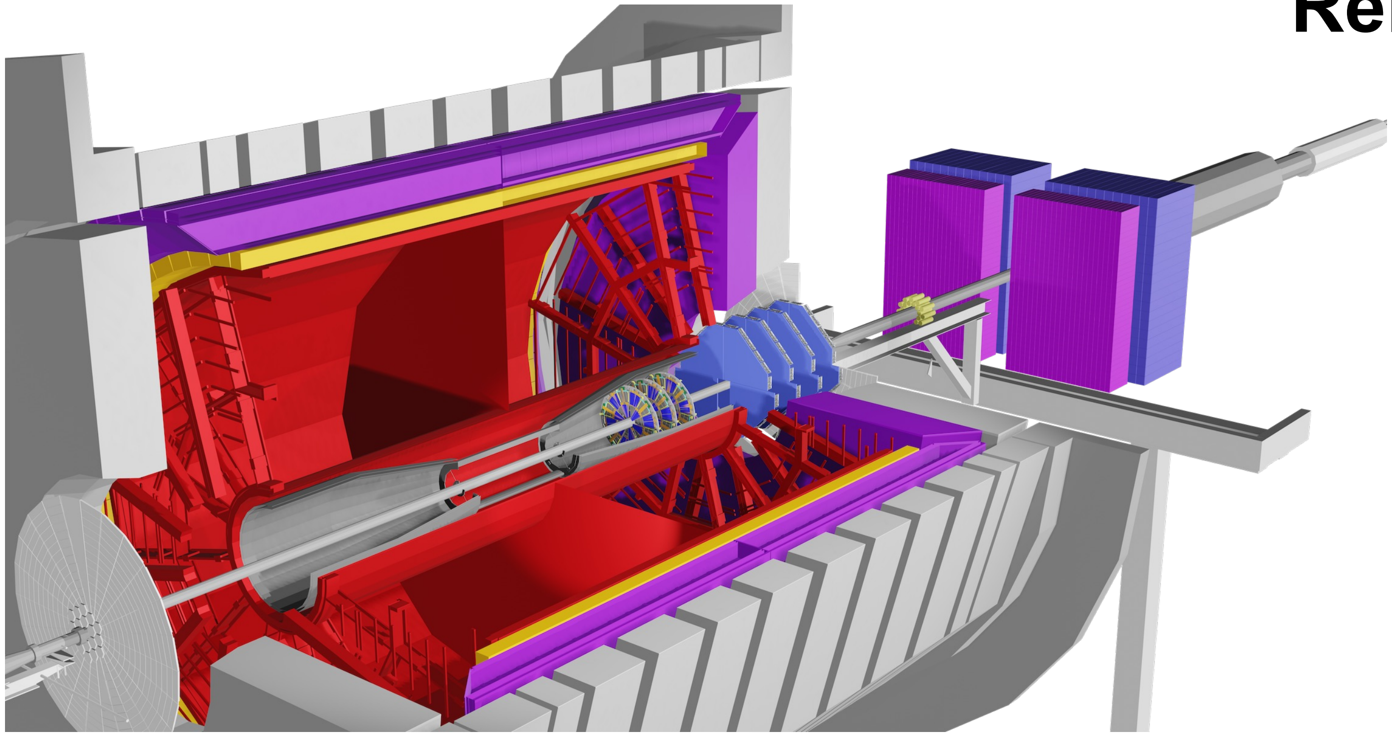
*Phys. Lett. B 679 (**2009**) 321-329*





Statistics was limited, coherent and incoherent were not separated, and with neutron selections

STAR experiment



Since 2022, STAR has forward detectors ($2.5 < \eta < 4.0$), which would be crucial to the RHIC Run 23-25 physics program

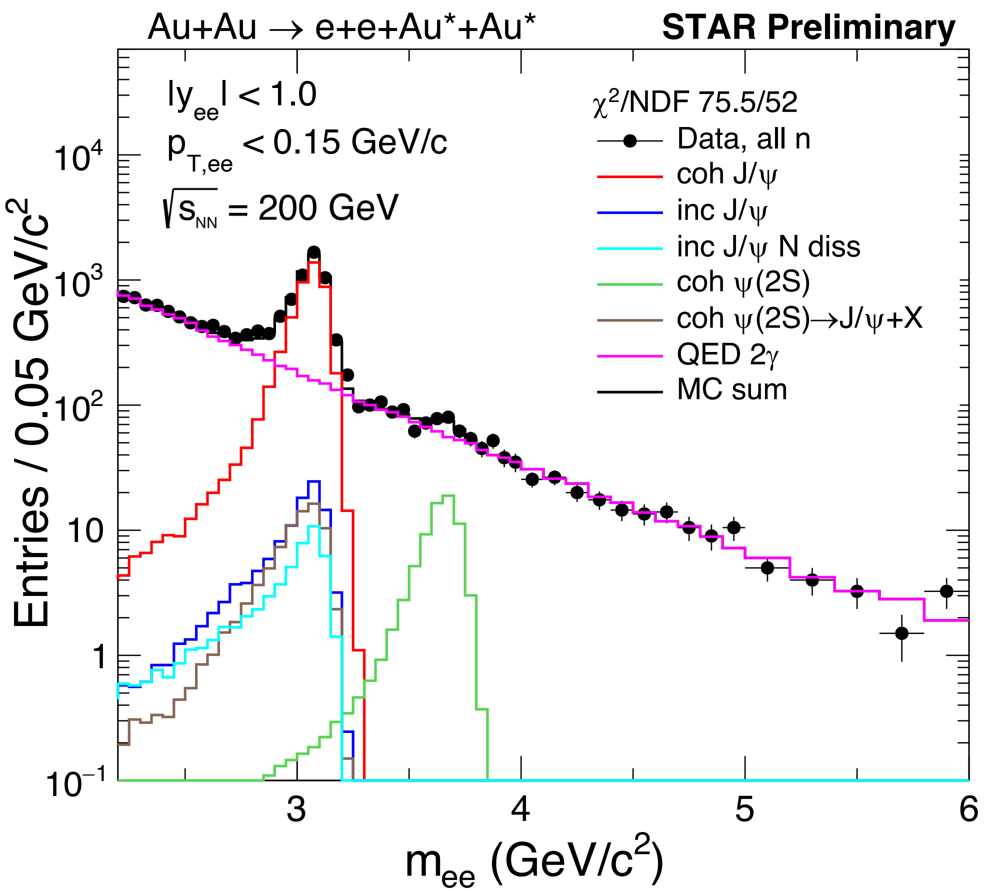
Relevant central detectors

Time Projection Chamber (TPC)

Time-Of-Flight detector (TOF)

Barrel EM Calorimeter (BEMC)

Measuring J/ψ in 200 GeV Au+Au UPCs



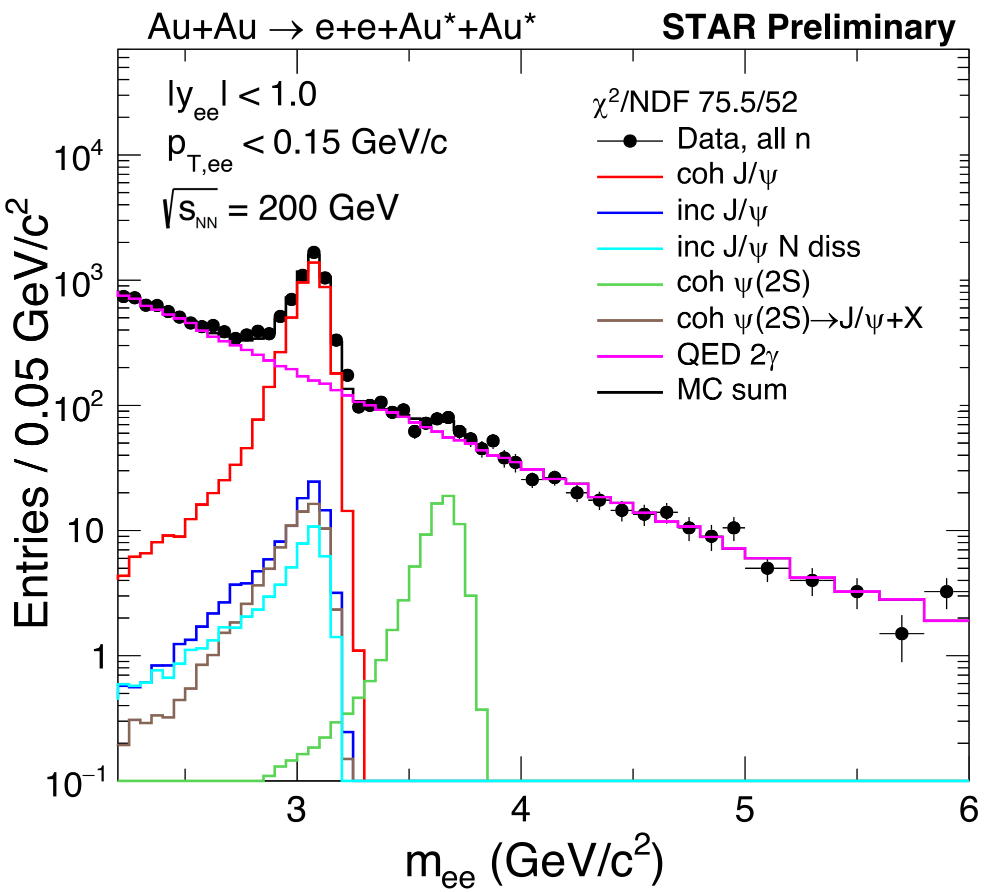
Data analysis:

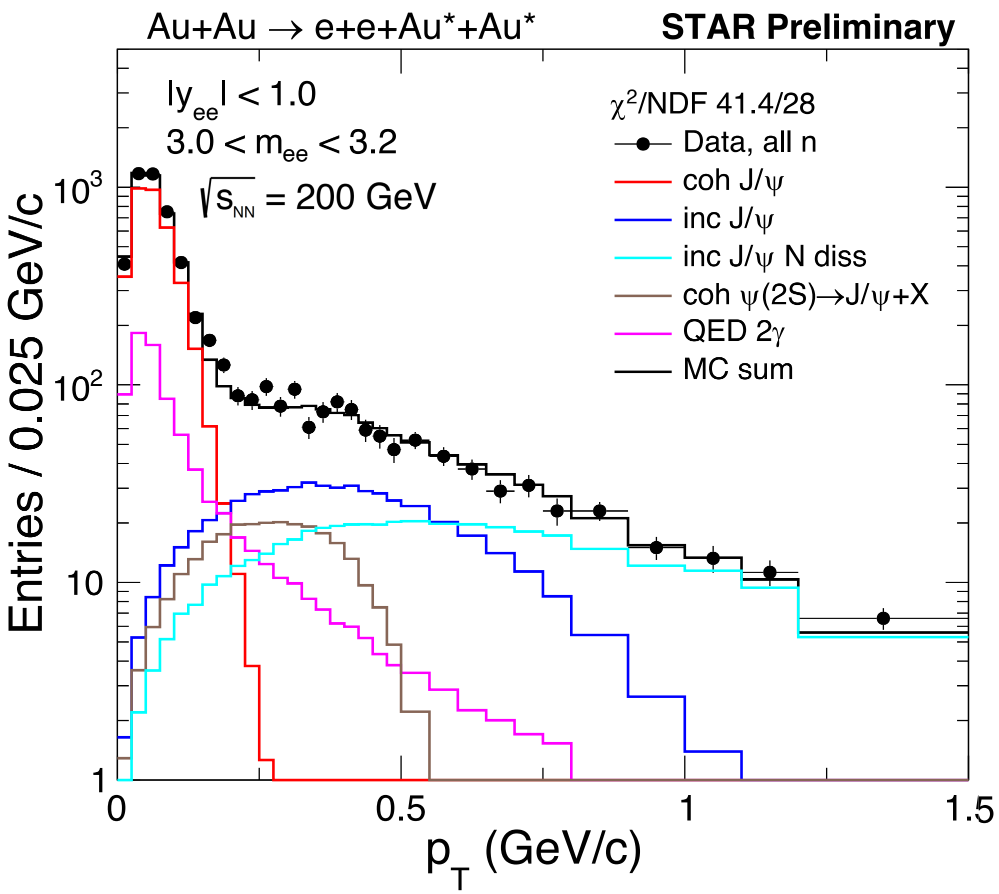
$J/\psi \rightarrow e^+e^-$
(|y| < 1.0 for J/ψ, electrons within |η|<1.0)

STAR PID (e.g., TPC, TOF) capability ensures high purity of electron candidates.

Different templates from STARLight and H1 *ep* data are used to describe the signal and backgrounds.

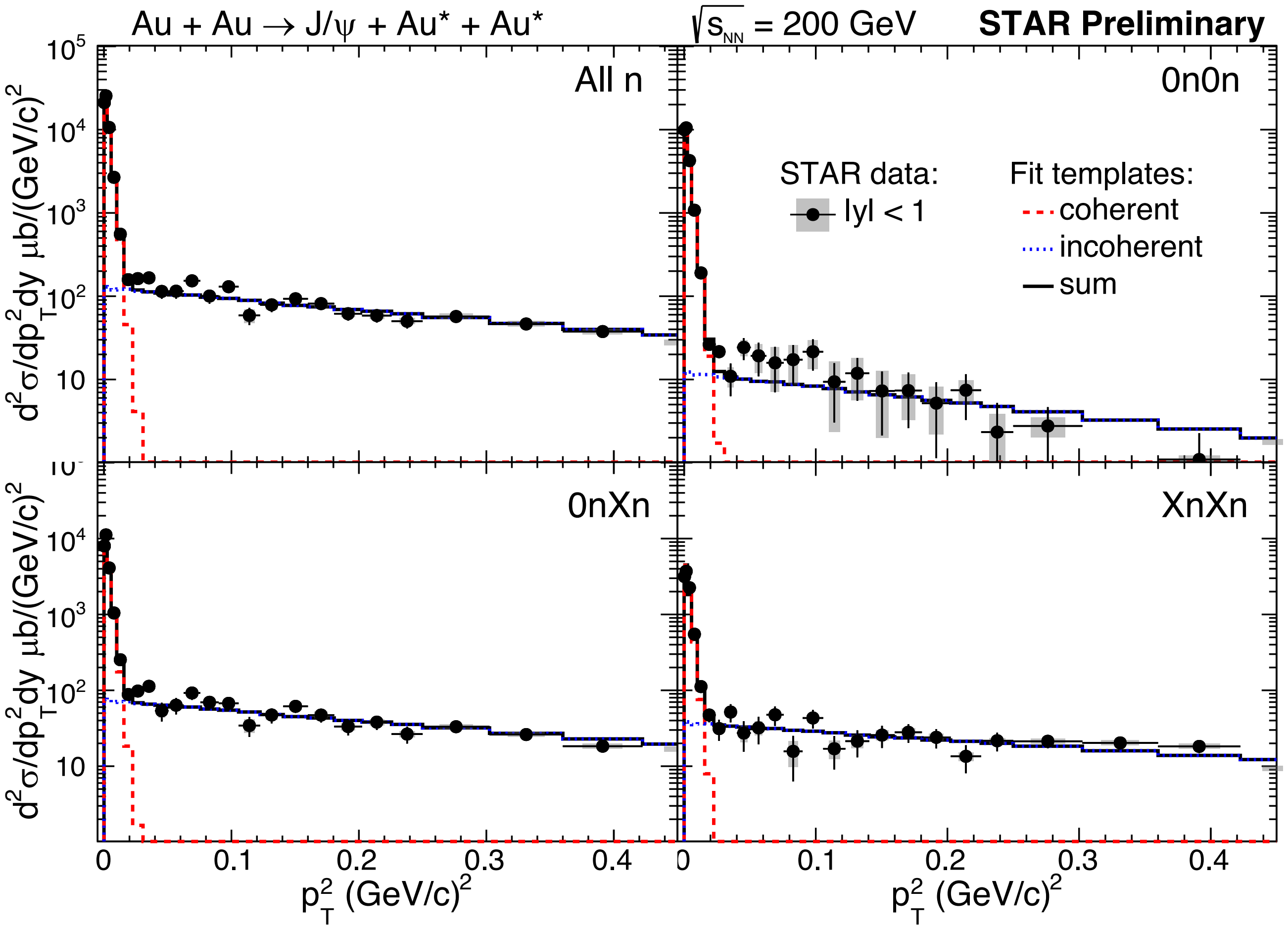
Measuring J/ψ in 200 GeV Au+Au UPCs





when $Q^2 \sim 0$, p_T of J/**ψ** is directly related to momentum transfer ($t \sim p_T^2$)

Separating coherent and incoherent J/ψ



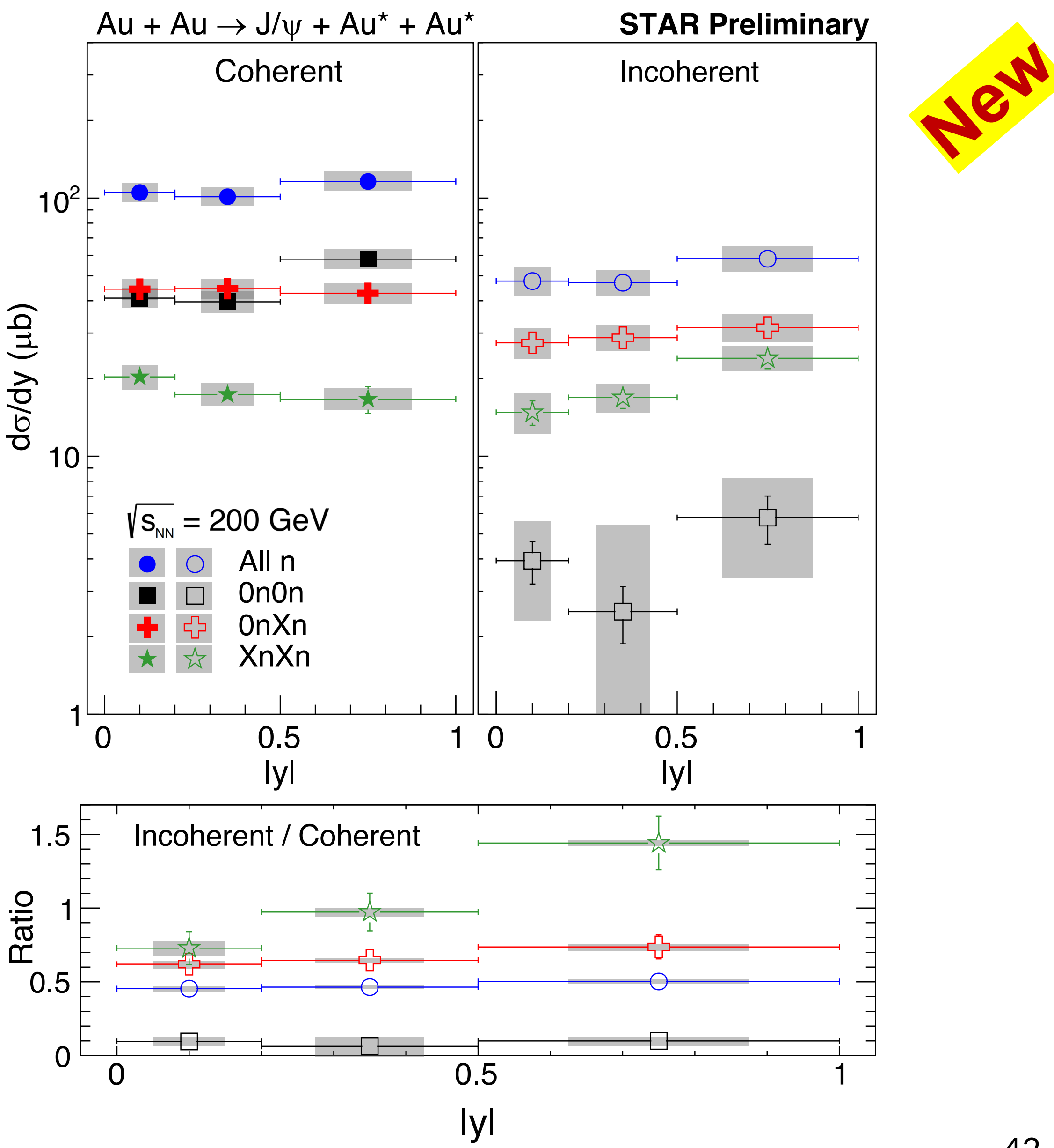
- Low momentum transfer (p_T^2) is dominated by **coherent** photoproduction.
- For incoherent production at low p_T^2, it is extrapolated using different templates.
- These differences, however, are small to the total incoherent production cross section.

First measurement of y-dependence of J/ψ at RHIC

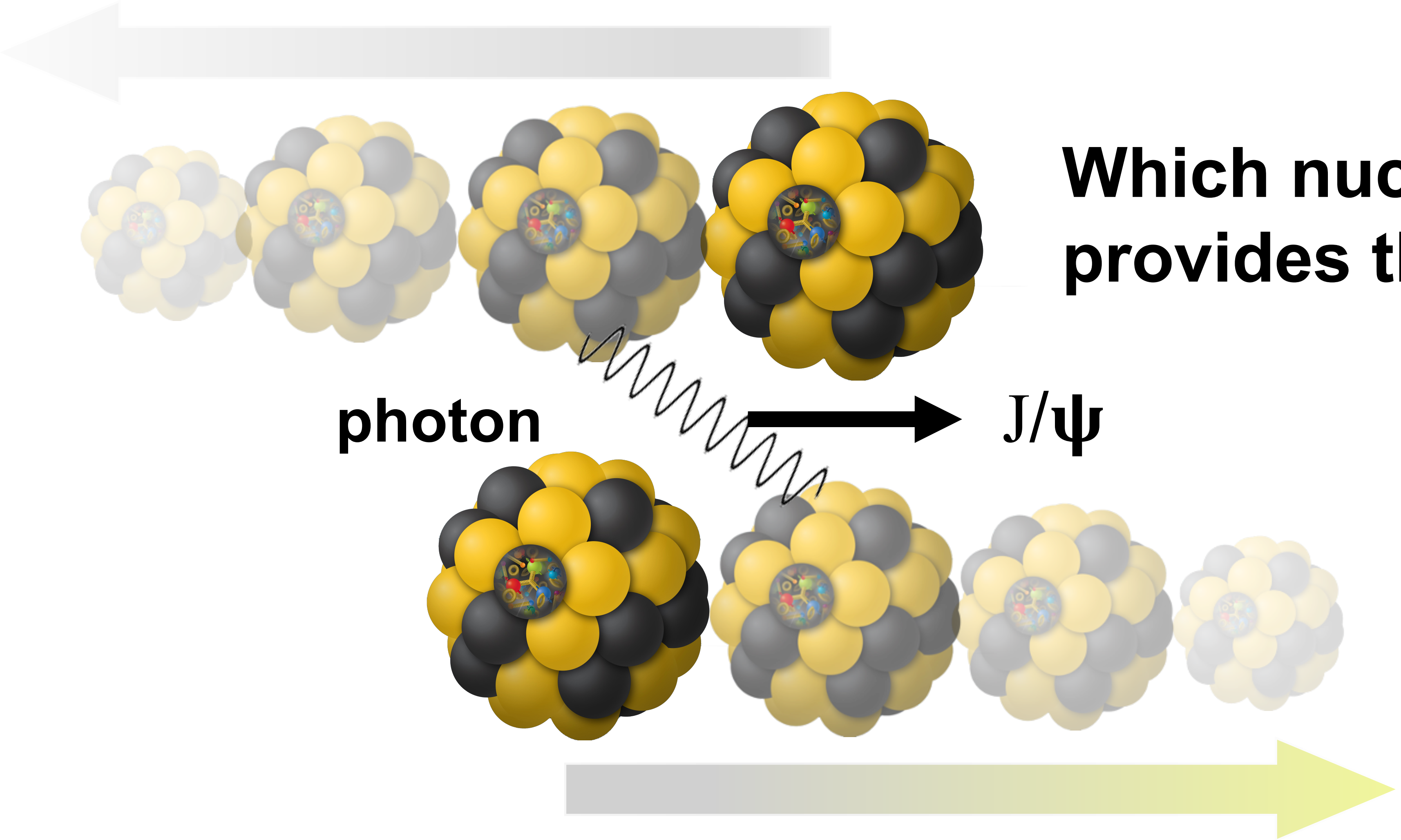
❖ Important measurements to constrain theoretical models

❖ Ratio of incoherent to coherent cross section largely cancels uncertainties both experimentally and theoretically

❖ New studies show this ratio is sensitive to nuclear structure and nuclear deformation (by W. Zhao et al. at a recent INT workshop)

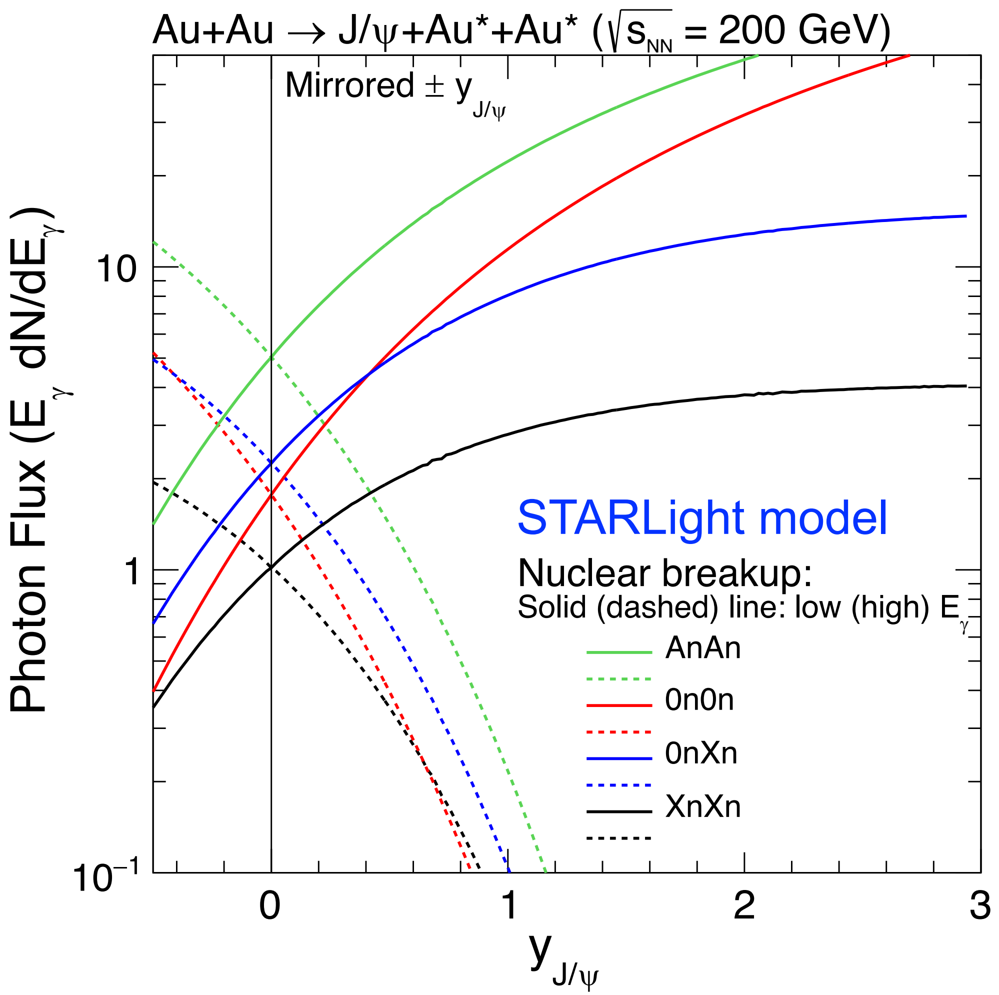


AuAu UPCs: two-source ambiguity



Which nucleus provides the photon?

Photon flux and neutron emissions for coherent J/ψ



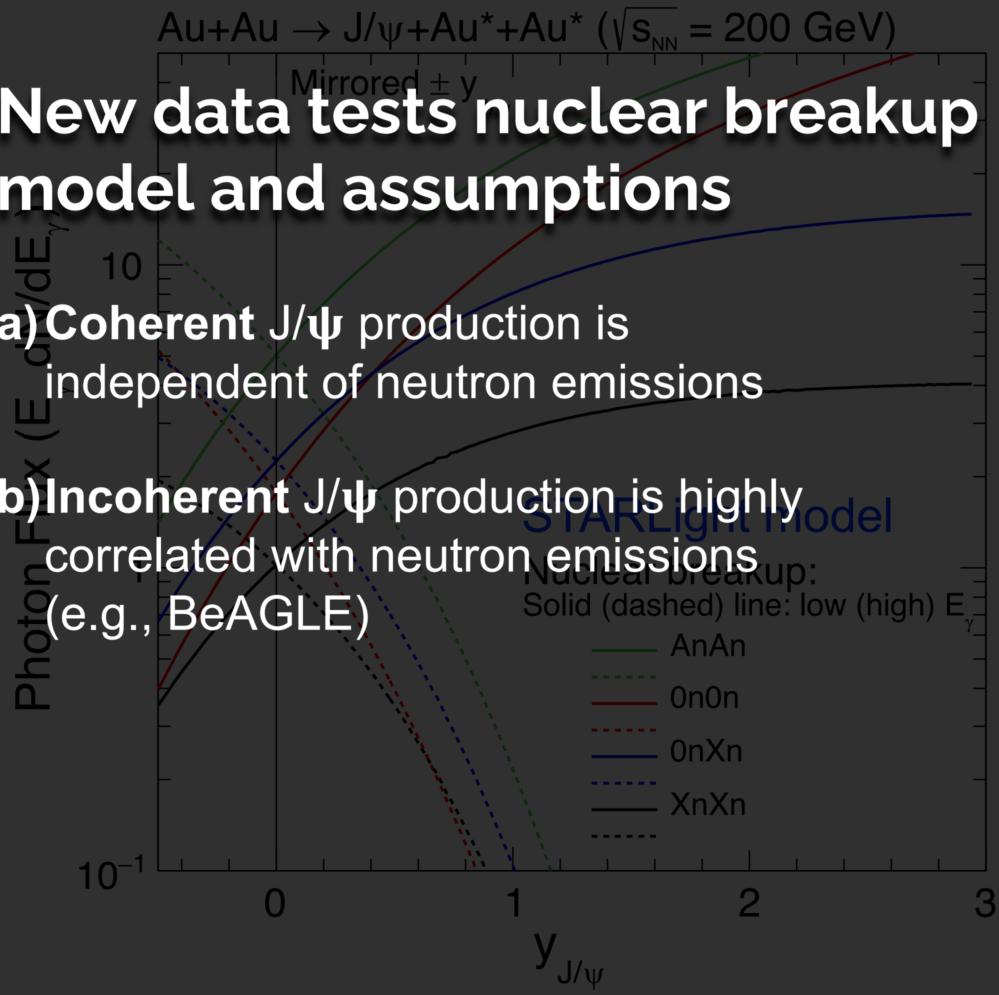
- If VM at rapidity $y \neq 0$, there is a high energy photon (k_1) candidate and a low energy photon (k_2) one;
- Different photon energies correspond to different flux factors (~number of photons)
- Different neutron emission classes associate with different flux factors

Neutron classes:

- **0n0n:** no neutron on either side
- **0nXn:** >=1 neutron on one side
- **XnXn:** >=1 neutron on both sides

Photon flux and neutron e

New



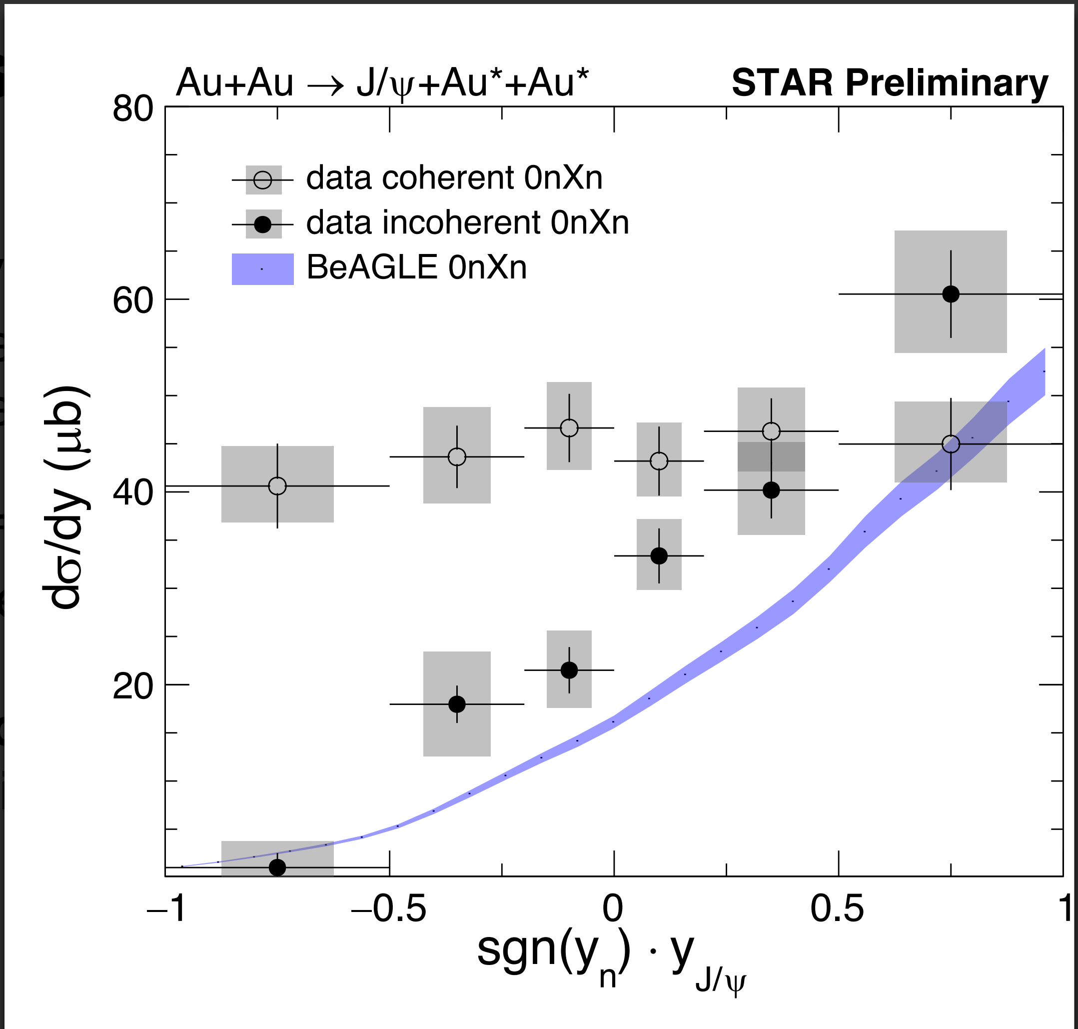
New data tests nuclear breakup model and assumptions

a) **Coherent** J/ψ production is independent of neutron emissions

b) **Incoherent** J/ψ production is highly correlated with neutron emissions (e.g., BeAGLE)

- If V
ene
ene
- Diff
diff
- **Eac**
emi

• **XnXn:** >=1 neutron on both sides



Reference to BeAGLE: *Phys. Rev. D* 106 (2022) 1, 012007

Neutron emission helps resolve the two-source ambiguity

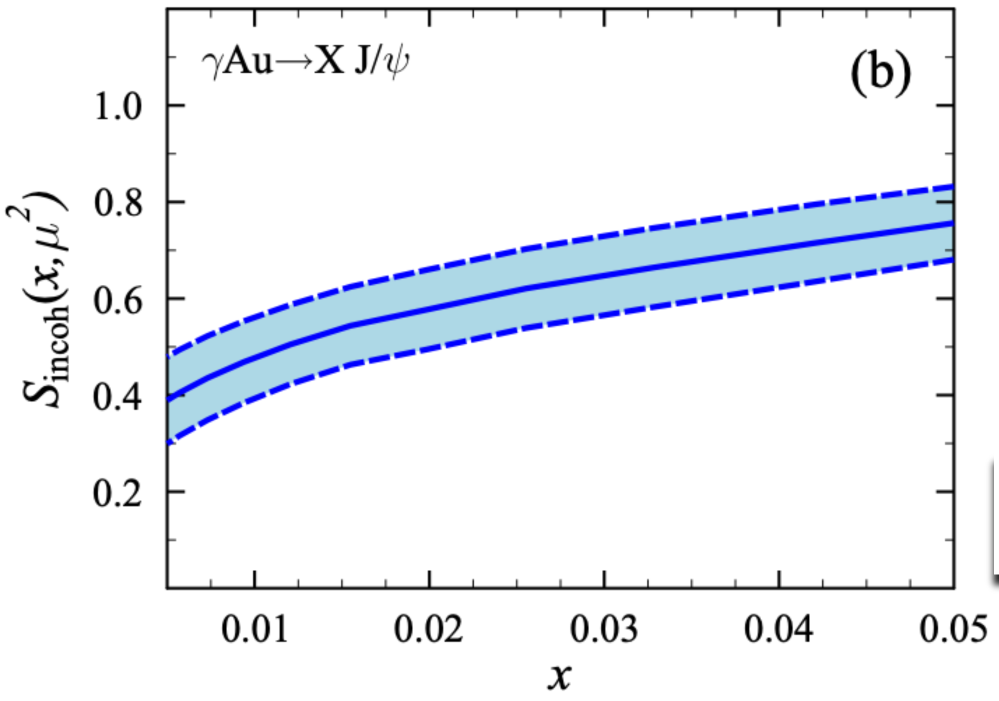
$$d\sigma^{AnBn}/dy = \Phi^{AnBn}_{T.\gamma}(k_1)\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_1) + \Phi^{AnBn}_{T.\gamma}(k_2)\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_2)$$

Measurements (slide 12) | Photon fluxes (slide 14) | Unknowns

Eur. Phys. J C (2014) 74:2942

Need to measure differential cross section in *y* and in neutron emission classes; **at least 2 equations to solve 2 unknowns.**

Shadowing in incoherent J/ψ photoproduction



This ratio is driven by multi-nucleon interactions, nuclear thickness function, diffractive parton distributions, etc.

(*Phys. Rev. C* 108 (2023) 2, 024904)

$$S_{\rm incoh}(x,\mu^2) = \frac{1}{A}\int d^2\mathbf{b}\, T_A(\mathbf{b}) \left[1 - \frac{\sigma_2(x,\mu^2)}{\sigma_3(x,\mu^2)}\left[1 - e^{-\frac{\sigma_3(x,\mu^2)}{2}T_A(\mathbf{b})}\right]\right]^2 .$$

Intuitively, the incoherent J/ψ production is the convolution of: J/ψ production off a nucleon inside of a nucleus ⊗ probability of the J/ψ survives on its way out of the nucleus.

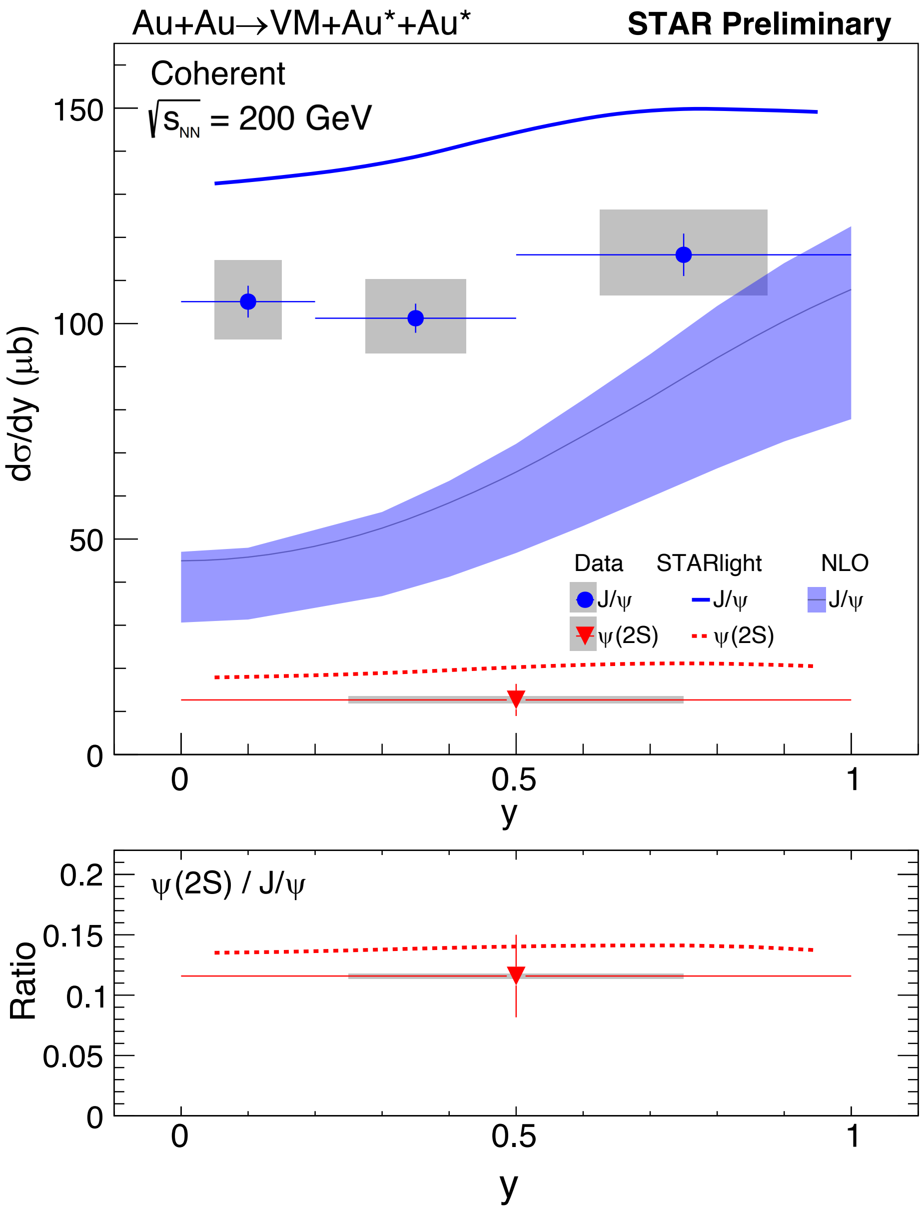
NLO calculation

Next-to-Leading Order (NLO) pQCD calculation, constrained **by the LHC data**

EPPS21 + scale at 2.39 GeV.
Only scale uncertainty shown.

Could not describe the STAR data at y = 0.

Reference to NLO pQCD calculation:
a) arXiv:2210.16048
b) Phys. Rev. C 106 (2022) 3, 035202



Special thanks to:

CGC: Heikki Mäntysaari, Farid Salazar, Björn Schenke
Sartre: Tobias Toll, Arjun Kumar
Nuclear shadowing: Vadim Guzey, Mark Strikman, Mikhail Zhalov
NLO pQCD: Topi Löytäinen et al.
Saturation observables: Brian Sun, Y. Kovchegov

For discussions and inputs.